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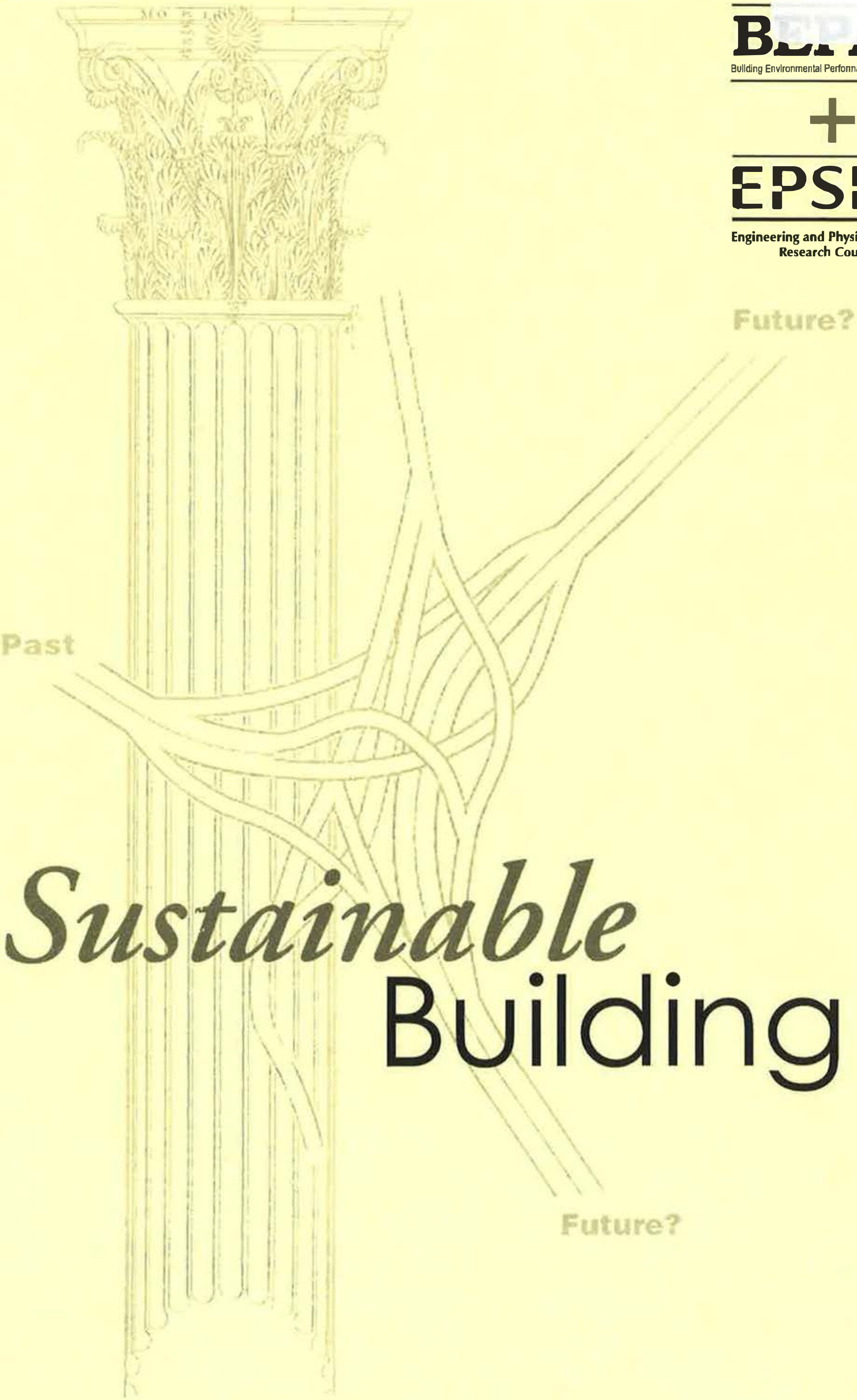

Sustainable Building

Proceedings of a mini-conference held on 5/6 February 1997 at Abingdon, Oxfordshire, UK and on http://www.iesd.dmu.ac.uk/BEPAC

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The Building Environmental Performance Analys
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in 1987 with the assistance of the Department
including the Science and Engineering Resea
Sciences Research Council, EPSRC), the primar
computerised methods. The club has arou
government agencies, computer software deve
researchers from the public and private sectors, u

As computer models have matured, their ability to
apparent. BEPAC's central interest is in the mode
renewable energy and are more comfortable. Th
research on building modelling, through its Ene
exploration continue to be uncovered the fundame
research is well established. The promotion of
important activity within BEPAC.

It is apparent, however, that many of the barriers t
and political, and that the decisions and actions o
impact on the broader energy and environment p
research to underpin these, are being used to h
evaluate the impact which their decisions might hav

More recently, therefore, the EPSRC has widened
now supports research on broader city-wide issues

The **Sustainable Building** conference has been c
industrialists and local authority representatives clos ... are to:

- inform policy makers and those concerned with building in cities about the research that is being undertaken; and to
- seek the views of local government and industry about the direction which future research might take.

The papers cover an extraordinarily wide field. Topics range from the effect of building density on travel patterns through smart meters and the design of healthy offices to the prediction of NOx emissions from boilers - a graphic illustration of the complexity of 'sustainability' and the far-reaching changes that will be needed in society to achieve it. Clearly, sustainability will remain a focus for debate and research for years to come.

It is encouraging that, having supported BEPAC in the early years, the EPSRC is now able to exploit BEPAC's strong industry-academia links to enable a conference like **Sustainable Building** to take place and help turn research into practical action.

I hope you find the papers interesting and informative.

Kevin J Lomas
Vice-Chairman, BEPAC

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Chilled ceiling and displacement ventilation environments: airflow, radiant asymmetry and thermal comfort effects

D L Loveday[1], K C Parsons[2] and S G Hodder[1], Loughborough University and A H Taki, De Montfort University[3]

Abstract

The paper presents the findings to date of an ongoing EPSRC-funded research contract. A typical chilled ceiling/displacement ventilation office has been created within a laboratory test room, in which the ceiling temperature can be varied over a typical range of working temperatures. For those conditions tested, it was found that the combination of a chilled ceiling with a displacement ventilation system could cause destruction of the displacement flow pattern at low ceiling temperatures. The thermal comfort of 128 test subjects (64 male, 64 female) was then measured in the test room over the range of ceiling temperatures. Vertical radiant asymmetry was found to have an insignificant effect of the thermal comfort of the seated occupants for the typical range of ceiling temperatures that would be encountered in practice. Furthermore, the Fanger thermal comfort model is shown to be capable of predicting the PMV of subjects in such environments, and preliminary results indicate that a ceiling temperature of 18°C is potentially the most acceptable. Analysis of data is continuing and a fuller picture of the design conditions required for comfort will emerge in due course.

Introduction

Energy consumption in buildings is responsible for about 50% of the UK's total carbon dioxide emissions, with a similar situation prevailing in other industrialised countries. In many industrial and commercial buildings the provision of comfortable space conditions has often been achieved through the use of air-conditioning, widely recognised as being an energy-intensive solution to the problem. Interest has therefore been kindled into the adoption of low energy techniques for the conditioning of office environments. One such technique is that of displacement ventilation. This has arrived in the UK from mainland Europe, and consists of the provision of a full fresh air supply to a space at low level, low velocity and at a temperature lower than that of the desired zone air temperature. Density differences cause the fresh air to form a layer over the floor; the air then rises as it is warmed by heat sources in the zone, and the convective plumes generated by these sources remove heat and contaminants which are extracted at ceiling level. The system is able to provide an environment of improved air quality as compared with the mixing of air which occurs in conventional HVAC systems (for the same air flow rate conditions); also, the same heat loads can be removed for a supply air temperature of typically 19°C as compared with one of 13°C in HVAC systems, thereby saving energy. As a result of thermal comfort limitations, namely that the vertical air temperature gradient should be less than 3°C per metre (ISO 7730, 1994), a displacement ventilation system is limited to removing a convective load of up to 25Wm^{-2} of floor area (Sandberg and Blomqvist, 1989). However, heating loads in offices frequently exceed this figure and so it becomes necessary to install an additional cooling mechanism, such as a chilled ceiling.

In a chilled ceiling system, cold water flows through pipework which is bonded to ceiling tiles, producing a typical ceiling tile surface temperature in the range 16-19°C. Chilled ceilings can remove heat loads of up to 100Wm^{-2} of floor area mainly by radiation, and are considered to enhance the

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thermal comfort sensation of occupants. When combined with displacement ventilation, the advantages offered by each system separately (improved air quality, enhanced thermal comfort) are claimed to be retained for the combined arrangement, but is this actually the case? A three-year research programme funded by the EPSRC is taking place at Loughborough University to answer this question; the aim of the research is to determine the design conditions necessary for occupant thermal comfort in such combination environments. The work is still continuing, but here we report findings to date on the following:

i) the effect of chilled ceiling temperature on the displacement air flow pattern, as determined from vertical temperature profiles,

ii) the validity of the Fanger model for predicting overall thermal comfort in chilled ceiling /displacement ventilation environment, and

iii) whether the vertical radiant asymmetry remains within acceptable limits for comfort.

We begin by describing the test facility set up for our investigation.

The test facility

This has already been described in Taki et al (1996), but is repeated here for convenience.

A test room has been constructed to act as an office environment, employing a chilled ceiling and displacement ventilation system (Figure 1). It is a light weight room 5.4m long, 3m wide and 2.8m high, and its four walls are clad with Frenger panels offering control of the wall surface temperatures. The chilled ceiling and displacement ventilation system is comprised of commercially available units. The chilled ceiling has a 90% active area and consists of 6 individual circuits connected in parallel. Each circuit, in turn, is comprised of 4 or 5 chilled panels connected in series, and the area of each circuit is approximately $2.5m^2$. The circuits can be activated individually or collectively. Displacement ventilation is provided by a semi-cylindrical wall-mounted diffuser fitted at one end of the room; this is supplied with fresh air which can be tempered and humidified prior to entry into the space.

The room is equipped with a window which overlooks the external environment, so as to preserve the impression of a normal office. However, the window is comprised of seven layers of glass, providing insulation from the external environment, and thus minimising temperature differences between wall and glass surfaces; this effect is enhanced by extending the water flow network to include the window itself. The test room is carpeted and furnished to a normal office standard, and can either be equipped with thermal dummies to simulate human heat sources (as used in the tests on displacement flow/chilled ceiling interaction) or can be used for thermal comfort tests involving human subjects.

All environmental parameters within the room are controllable; these include supply air flow rate, air temperature, relative humidity, mean radiant temperature and the surface temperature of the chilled ceiling. All surface temperatures in the room are measured using Type T copper/constantan thermocouples to a resolution of $\pm 0.2^{\circ}C$. The vertical air temperature profile in the room is recorded using eight radiation-shielded thermocouples (Type T) mounted on a column. The mean radiant temperature and the mean air velocity were measured at three heights (0.1m, 0.6m, 1.1m) above the floor using a Type 1213 Bruel and Kjaer Indoor Climatic Analyser. All environmental parameters were logged every 5 seconds and average values were calculated every 5 minutes.

Experimental findings: physical environment

In this part of the work, the effect of chilled ceiling temperatures on the displacement air flow pattern was determined. The experimental procedure adopted was to measure the vertical air temperature profile in the room for the following conditions:

- a fixed heat load of $62Wm^{-2}$ of floor area
- a fixed air flow rate of 3.9 air changes per hour for the displacement ventilation supply, which was at a constant temperature of $19^{\circ}C$
- a range of chilled ceiling surface temperatures, including one condition with the chilled ceiling switched off (i.e. displacement ventilation only).

Figure 2 shows vertical temperature profiles in the room for a range of ceiling temperatures at a fixed heat load of $62Wm^{-2}$. The corresponding profile for the case of the ceiling switched off, that is, displacement ventilation only, is also shown for comparison. It can be seen that at a ceiling temperature of $14^{\circ}C$, there is complete mixing of air throughout the room as shown by the almost vertical air temperature profile from floor to ceiling. This is caused by downward movement of cold air which destroys the displacement flow pattern, resulting in almost all heat load being removed by the chilled ceiling. In this situation, the average air speed in the room was found to be at its greatest compared with that measured for all other test conditions. As the ceiling temperature is increased, this allows the displacement flow to take place, but only to a height of about 1.1m above the floor. This differs from the flow pattern as seen for the case of displacement ventilation only (chilled ceiling switched off) as a result of downward movement of cold air currents. It can be concluded that the combined operation of the chilled ceiling and the displacement ventilation system could cause deterioration in air quality as a result of a diminished displacement flow pattern. Further confirmation of the effect of the chilled ceiling on displacement flow was obtained from smoke visualisation tests.

Experimental findings: human thermal comfort

Applicability of ISO 7730

This part of the work is concerned with determining whether the existing comfort standard ISO 7730 (1994) can be used for the prediction of thermal comfort in chilled ceiling/displacement ventilation environments, conditions which are significantly different from those which prevailed during the development of the Fanger comfort model and upon which the standard is based.

A total of 128 test subjects (64 males, 64 females), in the age range 21-60 years, took part in the experiment. The test room was furnished so as to provide four work places, each with a personal computer. Subjects were admitted to the test room in groups of four (2 males, 2 females) to carry out sedentary office tasks for a period of 3 hours. They were not allowed to move around inside the room, thus keeping their metabolic rate to the estimated value of $70Wm^{-2}$ (1.2 met). The subjects wore typical office clothing provided by the experimenters, which consisted of: male - long sleeve white cotton shirt and neck tie, mixed fibre trousers, cotton socks; female - long sleeve white cotton shirt (same type as males), mixed fibre knee-length skirt, 15 denier tights; subjects wore 'office-type' shoes (no sandals or training shoes). The clo value of both clothing ensembles was almost the same at 0.75 clo.

Four values of chilled ceiling surface temperature were selected for investigation (14, 16, 18 and $21^{\circ}C$), at two levels of relative humidity ('medium' and 'low' corresponding to approximately 50% rh and 25% rh, respectively). The remaining test room environmental conditions were kept constant at the same values as stated previously (displacement supply air temperature $19^{\circ}C$ at 3.9 air changes per hour). Each set of environmental conditions was experienced by a total of 16 subjects (8 males, 8 females). Subjects were asked to complete a thermal comfort questionnaire at 15 minute intervals throughout the 3-hour test, the data from the last 45 minutes being used in the analysis. From the questionnaires the actual mean votes (AMV) of the subjects were determined. Measurements of mean radiant temperature and mean air velocity were taken near the subjects at three heights (0.1m, 0.6m and 1.1m) above the floor at regular intervals during the test session; these data, together with readings of air temperatures and relative humidity were used to calculate values for the predicted mean votes (PMV) of the subjects using the Fanger model as presented in ISO 7730 (1994).

Figures 3 and 4 show the comparison of PMV and AMV at low and medium relative humidities, respectively. Note that each experimental point is the average of 16 subjects' responses. For both low and medium relative humidity levels, it can be seen that there is very good agreement between PMV and AMV values across the range of ceiling temperatures investigated. This shows that for the conditions tested (which are very typical design conditions), Fanger's model in the form of ISO Standard 7730 (1994) is valid for predicting the thermal comfort of sedentary occupants performing office-type tasks in chilled ceiling/displacement ventilation environments.

For the same set of conditions, Table 1 shows the corresponding local comfort sensations for different parts of the body, where 'w' and 'c' refer to being 'warm' or 'cool', respectively, with respect to neutral 'n'. In terms of the number of 'neutral' sensations reported by test subjects it would appear, at this stage, that a ceiling temperature of 18°C and a medium relative humidity is the most acceptable combination of conditions for occupant comfort in such environments. Note that these findings are for a displacement ventilation supply air temperature of 19°C at 3.9 air changes per hour. Further experimental data obtained for a range of supply air flow rates is still being analysed, and in due course a fuller picture of the design conditions required for thermal comfort in chilled ceiling/displacement ventilation environments will emerge.

Radiant asymmetry effects

In chilled ceiling environments, a temperature difference between the floor and the ceiling will produce vertical radiant asymmetry. A further set of experiments were undertaken to determine the effect of such radiant asymmetry on thermal comfort, and specifically whether this should led to the imposition of a design limit on ceiling temperature. Female subjects only were asked to take part in these experiments because our preceding work had shown that the females were generally more sensitive than the males to these thermal environments. Eight subjects, tested individually and wearing the clothing ensemble described previously, carried out sedentary office-type work with thermal dummies taking the place of the other human subjects. Ceiling temperatures of 22, 18, 14 and 12°C were investigated over a 3-hour period, the PMV for each condition being maintained at a calculated value of 'neutral' (as estimated from ISO 7730) by making small adjustments to the four wall surface temperatures in the test room (thus effecting room mean radiant temperature). In this way, any departure from neutrality of the subject's AMV would be the result of radiant asymmetry only.

The results are shown in Figure 5, where it can be seen that the vertical radiant asymmetry experienced within a typical chilled ceiling/displacement ventilation environment has an insignificant effect on the AMV of the test subjects. This is in agreement with findings obtained by Fanger et al (1985) for conventional environments.

Conclusions

Experiments concerned with environmental conditions and human thermal comfort have been conducted on a typically-designed chilled ceiling/displacement ventilation environment. For those conditions tested, the following conclusions may be drawn:

i) The combination of a chilled ceiling with a displacement ventilation system could cause destruction of the displacement air flow pattern at low ceiling temperatures (14-16°C). At higher temperatures (18-21°C), some displacement flow is present, but the stratified boundary layer is strongly suppressed. This could adversely affect air quality.

ii) ISO Standard 7730 (1994) is valid for predicting the thermal comfort of sedentary occupants performing office-type tasks in such environments.

iii) The radiant asymmetry experienced within a typical chilled ceiling/displacement ventilation environment does not significantly affect the thermal comfort of the seated occupant.

Analysis of data is continuing, and a fuller picture of the design conditions required for comfort in these environments will emerge in due course.

Acknowledgements

The authors express their gratitude to EPSRC for funding this research work and to Trox (UK) Ltd for the provision of equipment and assistance.

References

Fanger, P.O., Ipsen, B.M, Langkilde, G, Olsen, B.W, Christensen, N.K, and Tanabe, S. 'Comfort Limits for Asymmetric Thermal Radiation', Energy and Buildings 8, pp 225-236, 1985.

ISO Standard 7730, 'Moderate Thermal Environments - Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort', 1994.

Sandberg, M and Blomqvist, C. 'Displacement Ventilation in Office Rooms'. ASHRAE Transactions 5 (2), pp 1041-1049, 1989.

Taki, A.H, Loveday, D.L and Parsons, K.C. 'The Effect of Ceiling Temperatures on Displacement Flow and Thermal Comfort - Experimental and Simulation Studies', Proc 5th Int. Conf on Air Distribution in Rooms, 'Roomvent 96', Vol 3, pp 307-314, Yokohama, Japan, July 1996.

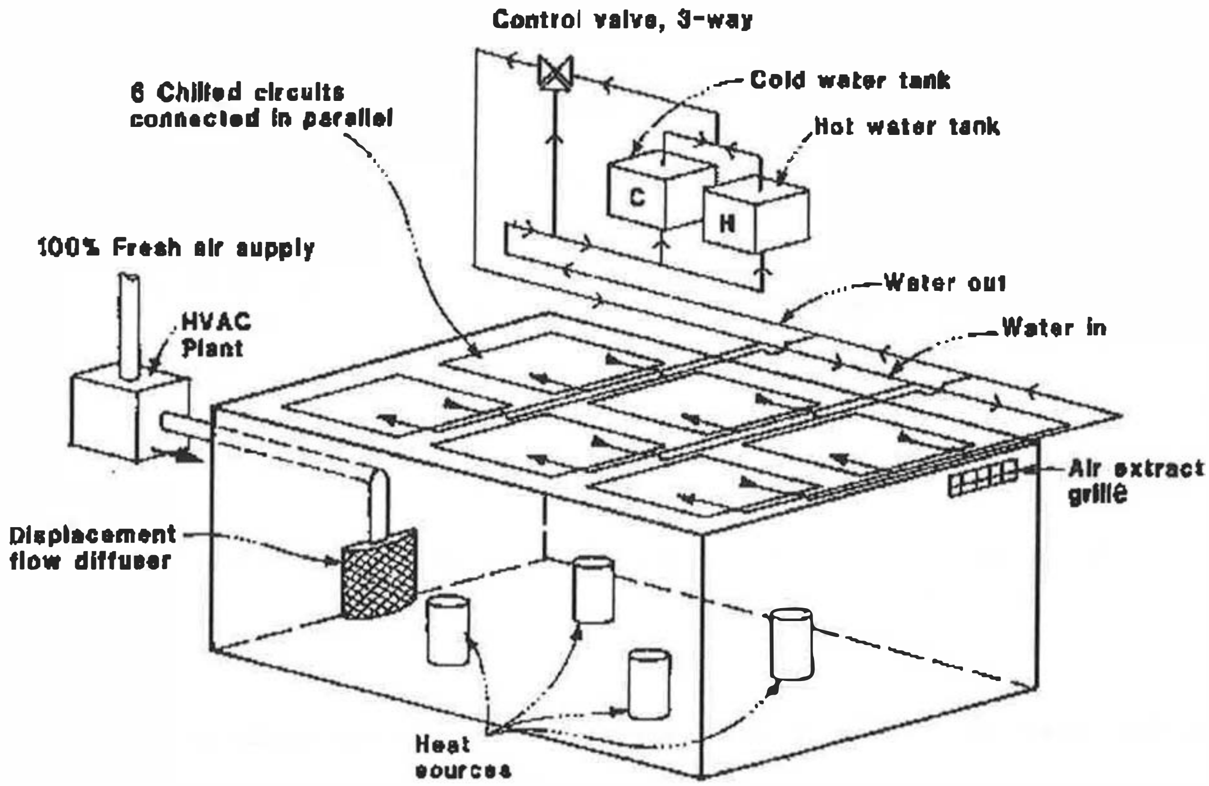

Figure 1: Illustration of test room

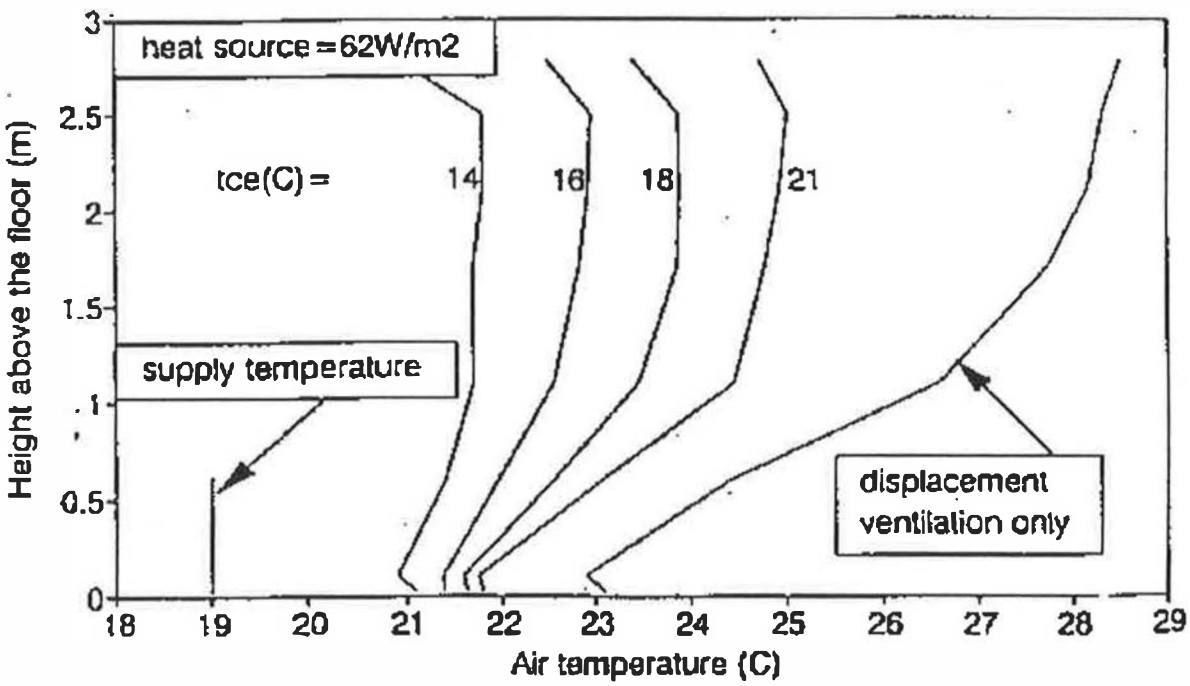

Figure 2: Air temperature verses height for a range of ceiling surface temperatures, t_{ce}, at a heat load of 62Wm^{-2}

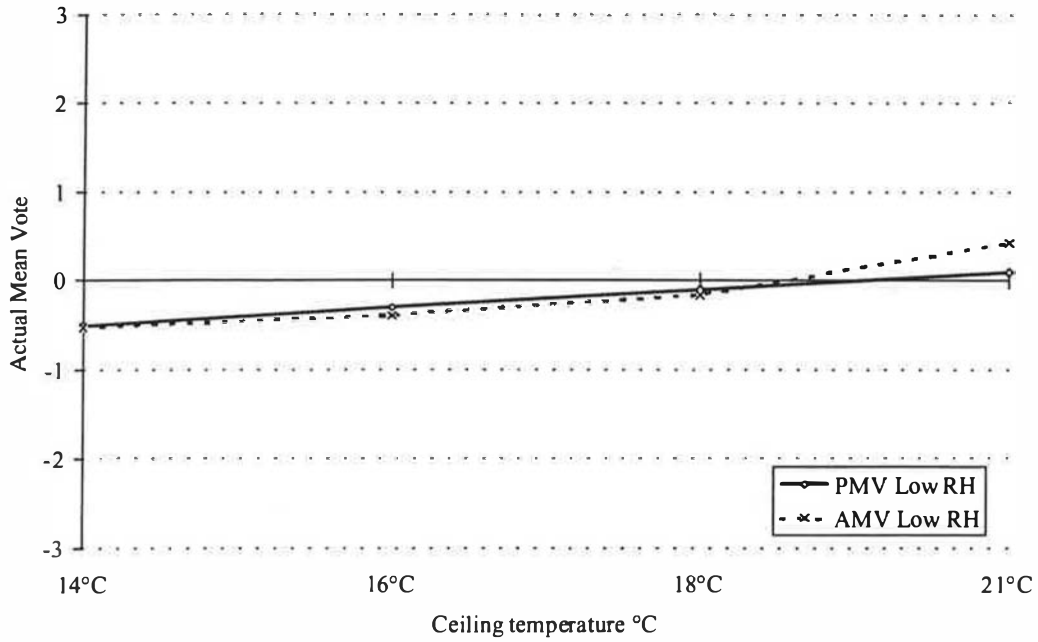

Figure 3: Comparison of AMV and PMV as a function of ceiling temperature, at low relative humidity, (N = 16 per condition)

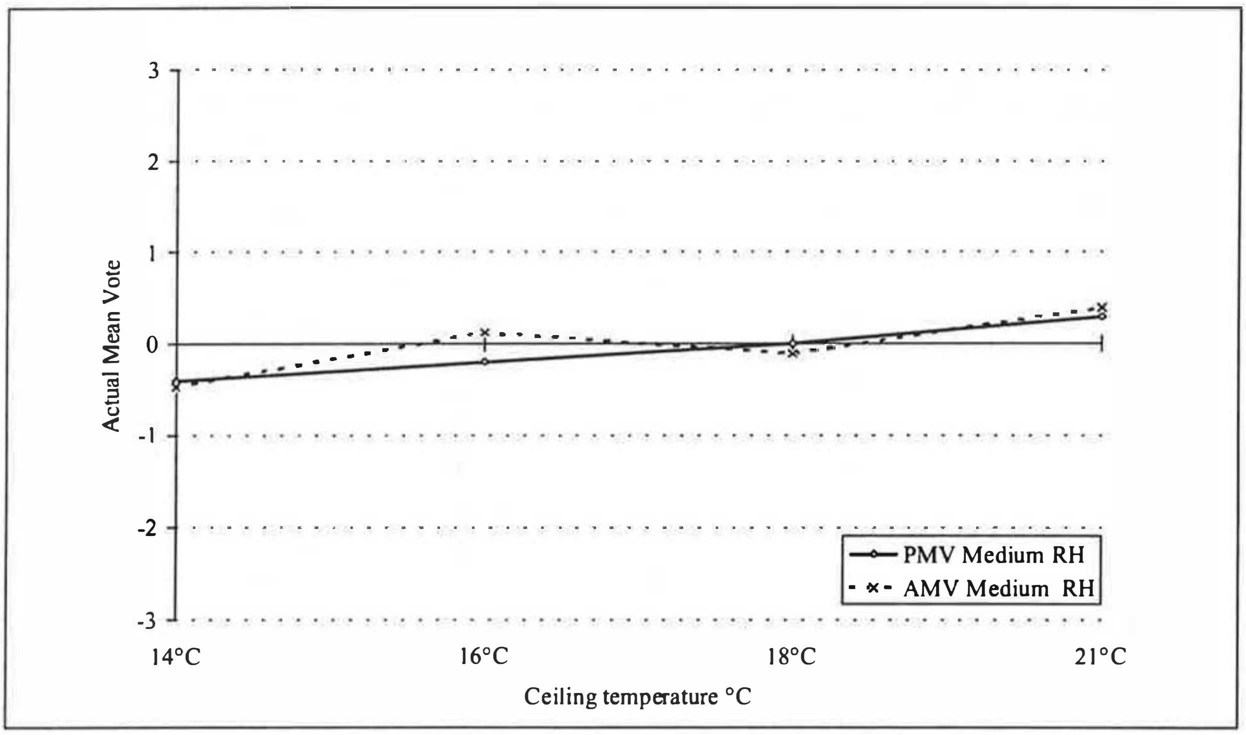

Figure 4: Comparison of AMV and PMV as a function of ceiling temperature, at medium relative humidity, (N = 16 per condition)

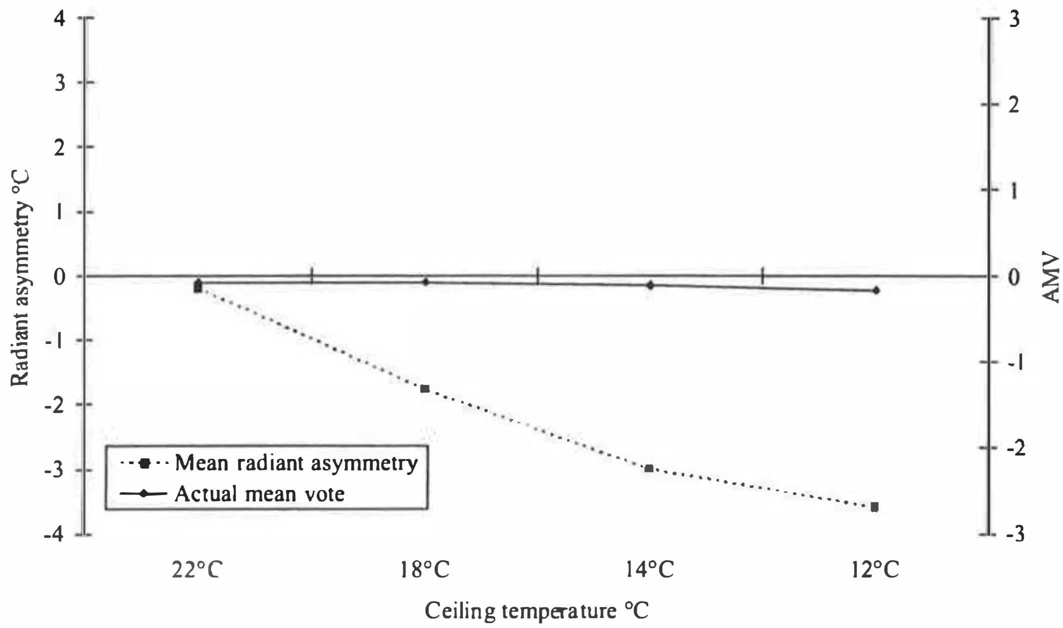

Figure 5: Effect of vertical radiant asymmetry on AMV for four ceiling temperatures.

Ceiling temperature °C	14		16		18		21	
Relative Humidity	25 % RH	50 % RH	25 % RH	50 % RH	25 % RH	50 % RH	25 % RH	50 % RH
overall	c	c	c	c	n	n	w	w
head	n	c	n	n	w	n	w	w
shoulders	c	c	c	c	n	c	w	c
trunk	c	c	c	c	n	n	w	w
arms	c	c	c	n	c	n	w	w
hands	c	c	n	c	c	n	w	w
above knee	c	c	c	c	n	n	w	w
below knee	c	c	c	c	c	n	n	n
feet	c	c	c	c	c	n	n	w

N = 16 per ceiling temperature/relative humidity combination

Table 1: Summary of the actual mean votes for chilled ceiling/displacement ventilation environments

Modelling temperature and human behaviour in buildings 1): Scoping Study

Fergus Nicol and Iftikhar Raja, Oxford Brookes University[1]

Summary

A scoping study is described whose aim was to develop an approach to the time-dependence of comfortable thermal conditions in buildings. The starting point of the study was that comfort conditions are known to change with indoor and outdoor conditions. The purpose of the study was to determine how quickly they change and the part which buildings play in the process.

Introduction

Current indoor temperature standards (ISO 1994, ASHRAE 1992) provide an estimate of the temperature which people will find comfortable based on work at constant temperatures carried out in climate chambers. The relevance of such results to comfort in the variable conditions found in naturally ventilated buildings has been questioned (Humphreys 1992, Nicol 1992). Temperature standards based on such work favour constant indoor temperatures only possible in highly-serviced, energy-hungry buildings. Recent questions about the consistency of the Fanger (1970) theoretical model on which many standards are based (Humphreys and Nicol 1996) emphasise the need to question standards such as ISO7730 (ISO 1994).

The adaptive approach to thermal comfort (Nicol and Humphreys 1972, Nicol 1993) is now widely accepted and the subject of a growing body of research. The finding on which the approach is based is that people adapt to the conditions which they experience in everyday life in such a way as to decrease the likelihood of discomfort. This is achieved by behavioural changes to their own thermal balance (by changes in clothing, posture etc) or by changes in their thermal environment. This means that people are generally comfortable at a temperature which approaches their everyday norm (Humphreys 1976) and which, less directly, is a function of the mean of the outdoor temperature (Humphreys 1978) in a relationship of the form:

$$T_c = a\,T_o + b \qquad (1)$$

where T_c is the comfort temperature and T_o is some measure of the outdoor temperature (see below).

This paper describes a project to explore the use of an adaptive approach to set design values for indoor temperatures in terms of T_o and to determine the best measure of T_o. The aim of the research is to provide standards for comfort which take account of the dynamic-interactive relationship between building and occupants. This adaptive approach would allow a wider interpretation of acceptable indoor environments thus encouraging the use of natural ventilation in buildings. It has been shown that by using an adaptive algorithm (Humphreys and Nicol 1995) to set control temperatures in highly serviced buildings it is possible to reduce the energy used for indoor climate control by as much as 25% (Wilkin 1995).

Time and comfort temperature

One problem with the interpretation of the adaptive approach is that the monthly mean of the outdoor temperature has been used to define the outdoor temperature T_o in equation 1. But a monthly

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measure of T_0 will not reflect changes in comfort temperature which occur within the month. This could result in conditions which are comfortable being interpreted as uncomfortable and vice versa. Humphreys and Nicol (1995) have proposed an algorithm for indoor temperature which uses the running mean of the outdoor temperature as a defining variable.

A second problem with the adaptive approach is that it can be misinterpreted to mean that almost any temperature can be found comfortable. In fact conditions for comfort are subject to social and physical constraints on the ability to adapt which depend on context. In essence the mechanism is a feedback between building and occupants driven by the climate. The relationship between comfort temperature and running mean temperature is effected by these constraints on the ability to adapt.

The main part of the work described in this paper was a comfort survey conducted over a period of almost two months to shed light on these problems. The experimental results are fully presented in Nicol and Raja (1996). They explore the effect of rate of change of outdoor temperature on comfort temperature indoors, on the way in which buildings react to outdoor temperature and on the way this effects the use occupants make of the environmental controls available to them.

Experimental procedure

A field survey was conducted in buildings at Oxford Brookes University over a period of seven weeks in August and September 1994. The 20 subjects who took part in the survey were administrative and academic staff of the university and post graduate students. They occupied four buildings on the campus. These buildings can be variously characterised as lightweight or of mixed heavy and lightweight construction. One building was air conditioned,.

The thermal environment (air and globe temperatures, relative humidity and air movement) close to each subject was monitored at intervals of a quarter of an hour and recorded using a small data-logger. Subjects were asked to fill in a form three times a day (morning, midday and afternoon) to record their comfort vote, thermal preference and skin moisture together with their clothing, activity and use of thermal controls (use of blinds/curtains, opening of windows/doors, use of fans, heaters etc.). Meteorological data were obtained from the Radcliffe observatory (about 2 km distant). Comfort vote was recorded on the seven-point Scale based on that of Bedford (1936) and the preference vote on a five-point scale similar to that of McIntyre (1980)

Analysis of the results

The analysis of the results of the experimental results was in three parts:

- calculation of comfort temperatures, running mean outdoor temperature and other basic statistics
- analysis to show how comfort temperature changes with time and its relation to conditions indoors and outdoors
- analysis of the way in which building temperature varied with time and of the use of controls by building occupants

Calculation of comfort temperature and running mean temperature

The data were consolidated to provide datasets (Nicol 1993) of simultaneous subjective, environmental and meteorological data. An estimate of the temperature which subjects would find comfortable was made from the comfort vote C and the globe temperature T_g using the method suggested by Griffiths (1990):

$$T_c = T_g - 3C \tag{2}$$

The relationship gives the temperature which the subject will find comfortable with no change of clothing or metabolic rate.

The theoretical value of the exponentially-weighted running mean temperature for day n (${}^{n}T_{rm}$) is calculated from the series:

$${}^{n}T_{rm} = (1-\alpha)\{{}^{(n-1)}T_{od} + \alpha.{}^{(n-2)}T_{od} + \alpha^{2}.{}^{(n-3)}T_{od} + ..\} \qquad (3)$$

where ${}^{n}T_{od}$ is the mean outdoor temperature for day n and α ($0 \le \alpha \le 1$) is a time-constant. Each day's value of T_{rm} can be calculated from that of the previous day using the simple formula:

$${}^{n}T_{rm} = (1-\alpha).{}^{(n-1)}T_{od} + \alpha.{}^{(n-1)}T_{rm} \qquad (4)$$

The mean outdoor temperature (T_{od}) each day was calculated from the data obtained from the Radcliffe Observatory. The running mean temperature (T_{rm}) was calculated using the mean value of the temperature for each day of the survey.

To calculate values of T_{rm} an assumption must be made about the value for the constant α. A larger value for α implies a greater weighting for values of T_{od} in the past. The theory approximates to that of radioactive decay with the half-life of T_{rm} given theoretically by $0.69/(1-\alpha)$ (Humphreys 1972). Table 3.1 shows the theoretical half-life associated with selected vales of α.

Values of T_{rm} were calculated using different values of the constant α. Values used for α varied from 0.05 at intervals of 0.1 to 0.95 with extra interpolations at 0.7, 0.8 and 0.9. Figure 1 shows the value the mean outdoor temperature and the running mean temperature (T_{rm}) for each day of the survey and for selected values of α.

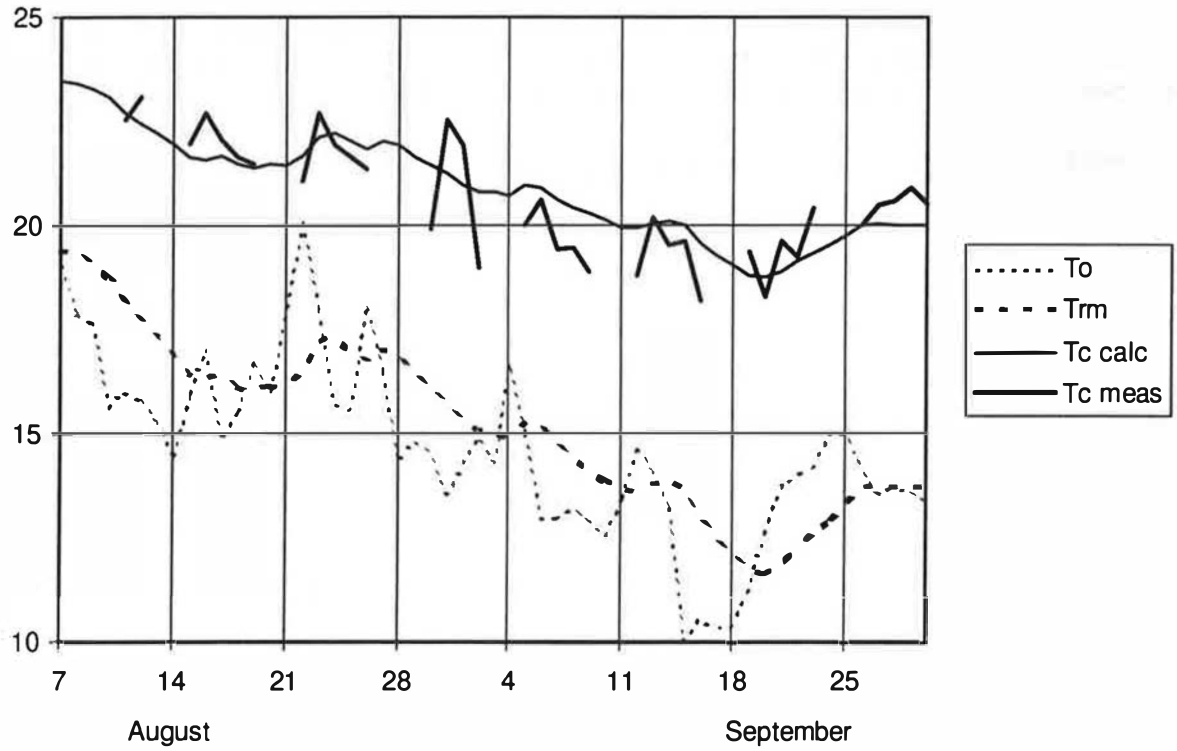

Figure 1: changes in comfort temperature and outdoor temperature during the survey (all buildings)

Change of comfort temperature with time

The was found to be a continuous change of the comfort temperature over the period of the survey (Figure 1) which generally reflected the drop in outdoor temperature towards autumn, though not its short-term changes. This suggests that a running mean of the outdoor temperature will be an appropriate measure of comfort temperature.

The first concern was to find out which value of α gives the best correlation between comfort temperature and outdoor running mean temperature. The mean value of the comfort temperature for all subjects who took part on any day was calculated by finding the mean values of C and T_g and substituting them in equation 2. This value of comfort temperature was correlated with different values of T_{rm}. The results are shown in Figure 2 in which the correlation coefficient r for T_c on T_{rm} are plotted for different values of α. The maximum value of r is at α_{max} = 0.8. A similar process was used to find the value of α for maximum r of clothing insulation on T_{rm} and give a comparable value for α_{max}. The regression equations for daily mean comfort temperature T_c and clothing insulation (I_{clo}) calculated from standard tables (McCullough et al 1985) are:

$T_c = 0.602T_{rm} + 11.7$ (r = 0.79) (5)

$I = 1.28 - 0.035T$ (r = 0.87) (6)

Figure 2: Change in correlation coefficient r for clothing insulation (I_{clo} open symbols) and comfort temperature (T_c filled symbols) on running mean temperature (T_{rm}) for different values of the time constant a NOTE: the square of r is used to exaggerate the change

Indoor temperature and use of controls

A similar process can be used to evaluate α_{max} for indoor temperature as a function of outdoor running mean. As expected the value of α_{max} is much smaller for buildings than for people giving a value of 0.35 overall, but of only 0.05 in the lightweight building. In the case of one basement room however, the value of α_{max} was 0.7 and discomfort in this room was minimum (6%) of all the buildings surveyed.

Although some subjects never made use of window opening, subjects in rooms prone to overheating often used window opening as a means of cooling them down. An analysis was made of the dependence of window opening on instantaneous outdoor temperature T_{oi}. The relationship between the proportion of windows open P_w (in %) and T_{oi}, obtained by regression analysis was:

$P_w = 6T_{oi} - 66$ (limits: $0 \le P_w \le 100$, r = 0.9) (7)

The outdoor temperature is a better measure than the indoor temperature: High indoor temperatures can be caused by the lack of an open window as well as providing an incentive to open it: the causal relationship is therefore muddled.

Subjects with blinds or curtains on their windows used them against glare rather than overheating. The use of blinds correlates to the solar intensity (r = 0.38) and not on the outdoor temperature with which it is practically uncorrelated.

Discussion and conclusions

The aim of this work is to provide simple rules for deciding whether a building with a variable indoor climate will prove comfortable. Current Standards tend to assume that the required indoor temperature is not affected by the weather outdoors except for a small seasonal difference. They also assume that the indoor temperature can be controlled.

Indoor temperatures in naturally ventilated buildings change in a way which is semi-random. The outdoor weather has a random variation about a more predictable mean. The indoor temperature reacts to this in a way which can be predicted from the characteristics of the building but includes many semi-random elements (occupancy, wind speed, window opening etc.).

To achieve the aims of the project we need a method to calculate the temperatures in buildings, both as an expected temperature and as a probabilistic variation about it. This research provides a method for forecasting the indoor temperatures which people will find comfortable. It could be used to classify buildings in terms of the predicted percentage discomfort.

The pilot study has confirmed that a relationship exists between the running mean of the outdoor temperature and the comfort temperature indoors. The project also threw light on the way in which building occupants use the controls at their disposal. In particular the finding that the probability of open windows in buildings prone to overheating is related to the outdoor temperature. Such relationships could be incorporated, even in simple simulations such as the admittance method (Louden and Danter 1965), to give a most likely indoor temperature and an expected distribution about it. Dynamic building simulations can be used to play a crucial role in the evaluation and application of Standards based on an adaptive algorithm.

Eventually the risk of discomfort could be assessed a variety of typical buildings. This can be done by modelling the range of indoor temperatures which result from different outdoor conditions and using the algorithm to assess whether the comfort zone falls within the range of conditions predicted. The adaptive approach shows that occupants will attempt to ensure their own comfort if this is within the range of options open to them.

Another use for the adaptive algorithm is in the control of air conditioning systems. Wilkin (1995) has shown that by using an algorithm relating indoor set-points to outdoor conditions, energy savings of up to 25% are possible.

The research described provides a framework for standards for comfort which take account of the dynamic-interactive relationship between climate, buildings and occupants. It is expected that the exact algorithm will be modified by the characteristics of the building, its control systems and other pertinent inputs such as management style. A full research programme is now under way using 12-month surveys of some 800 occupants of 17 buildings in Oxford and Aberdeen. This programme is described in the second part of this paper

References

ASHRAE 1992 *Thermal environmental conditions for human occupancy - ANSI/ASHRAE standard 55-1992* Amer Soc of Heating, Refrigeration and Air-conditioning Engineers, Atlanta.

Bedford, T 1936: *The warmth factor in comfort at work: MRC Industrial Health Board Report No 76* HMSO

Fanger P.O.1970: *Thermal Comfort:* Danish Technical Press

Griffiths 1990: *Thermal comfort studies in buildings with passive solar features; field studies:* report to the Commission of the European Community, ENS35 090 UK

Humphreys, M. A. 1972: Clothing and comfort of secondary school children in summertime. *Proc. CIB commission W45 symposium - Thermal comfort and moderate heat stress.* HMSO, London.

Humphreys M. A. 1976: Field studies of thermal comfort compared and applied: *Building Services Engineer 44*.

Humphreys M.A. 1978: Outdoor temperatures and comfort indoors, *Building Res. and Practice, 6 (2).*

Humphreys M.A. 1992: Thermal comfort, climate and buildings, *proc 1992 World Renewable Energy Congress* Pergamon, London

Humphreys M and Nicol JF 1996: Conflicting criteria for thermal sensation within the Fanger Predicted Mean Vote equation: *CIBSE/ASHRAE Joint National Conference '96:* Chartered Institution of Building Services Engineers, London

Humphreys M and Nicol JF 1995: An adaptive guideline for UK office temperatures, in *Standards for thermal comfort, indoor air temperature standards for the 21st century (eds Nicol, Humphreys, Sykes and Roaf)*, E and FN Spon, London.

ISO 1994 *Moderate thermal environments - determination of the PMV and PPD indices and specification of the conditions for thermal comfort - ISO standard 7730*. International Standards Organisation, Geneva.

Loudon A.G and Danter E. 1965, Investigations of summer overheating *Building Science 1 (1) 87-94.*

McCullogh E. A; Jones P.E. and Huck J. 1985, A comprehensive data base for estimating clothing insulation: *ASHRAE Trans 91(24) 29-4.*

McIntyre D. A. 1980, *Indoor climate*, Appl. Sc. Publ. Ltd. London

Nicol J.F 1992: Time and thermal comfort. *proc. 1992 World Renewable Energy Congress,* UK

Nicol JF 1993: *Thermal comfort, a handbook for field surveys toward an adaptive model*, University of East London.

Nicol, J.F and Humphreys M.A. 1972. Thermal comfort as part of a self-regulating system. *proc CIB commission W45 symposium - thermal comfort and moderate heat stress (ed Langdon et al) HMSO, London.*

Nicol JF, Jamy GN, Sykes O, Humphreys MA, Roaf S and Hancock M 1994: *A survey of thermal comfort in Pakistan, toward new indoor temperature standards.* School of Architecture, Oxford Brookes University.

Nicol JF and Raja IA 1996: *Thermal comfort time and posture, exploratory studies in the nature of adaptive thermal comfort*, School of Architecture, Oxford Brookes University, Oxford OX3 0BP.

Nicol JF, Raja IA and Alauddin, A 1997: *A survey of thermal comfort in Pakistan II, toward new indoor temperature standards.* School of Architecture, Oxford Brookes University (in press).

Wilkin, J P 1995: Adaptive comfort control for air conditioned buildings. *CIBSE National Conference '95:* Chartered Institution of Building Services Engineers, London

New guidelines for the design of healthy office environments

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Background to the study

During the decade preceding the study, numerous reports had occurred in both the popular and academic press concerning a range of low level symptoms amongst occupants of modern office environments, which together became known as Sick Building Syndrome. Investigations of these reports suggested a considerable variety of possible causes for the symptoms[1], ranging from poorly configured and maintained building services, through a host of environmental and organisational factors, to occupant characteristics and group dynamics. In particular, from the point of view of the research reported in this paper, one investigation (Wilson and Hedge, 1987)[2], was of considerable relevance. Taking the finding from the BUS study that the majority of the unhealthy buildings in its large sample were air conditioned it was not unreasonable to conclude that there was something inherent in air conditioning that generated the symptoms. In this climate the research team, with the support of the Science and Engineering Research Council (SERC) and the Department of Industry (DTI) through the LINK initiative, set out to determine what it was about HVAC systems and their operation that accounted for the noted ill health of occupants in air conditioned office buildings. Based upon such an investigation the aim was to generate guidelines for the design and operation of healthy of offices in the future.

Nine multidimensional building case studies, involving eleven organisations, were performed in accordance with the methodology developed during the project's pilot stage. The investigated buildings were selected from a list of nearly one hundred candidates. In choosing the buildings attention was paid to selecting HVAC systems that either represented current good practice and that were free of obvious design problems, or that offered the possibility of important lessons for the future. In particular, two buildings were selected because of the age of their systems and the potential this offered for lessons concerning refurbishment. In addition to examining the HVAC system each investigation considered the building's utilisation of space, workspace environmental conditions, and occupant health, attitudes and behaviour. 2191 occupants from a population of 3285 participated in the study by completing a questionnaire. The responses to these questionnaires, and subsequent diaries, together with the data from extensive physical monitoring form the basis of the analysis and conclusions presented in this seven page summary and its parent technical report.

Aims of the study

The aims of the study were :-

- To determine the specific factors associated with HVAC systems which may be responsible for symptom occurrence.
- To determine the relationship between the environmental conditions produced by the HVAC system and symptom reporting.
- To identify the role other built environment, spatial, organisational and personal factors play in symptom reporting.
- From this understanding to generate design guidelines that would help improve occupant health in air conditioned offices in the future.

In developing the methodology from these aims, the team sought to respond to a fundamental hypothesis

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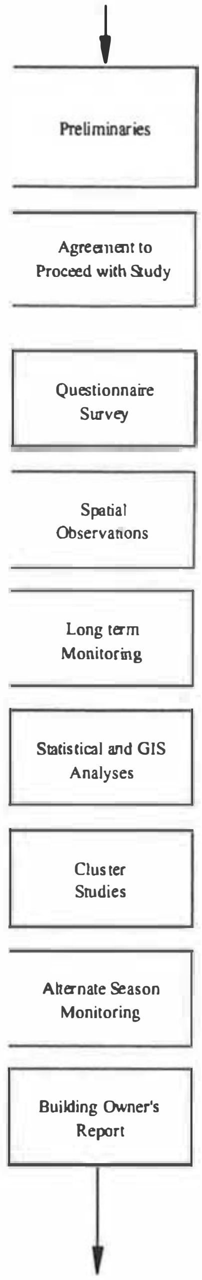
that health was the outcome of a complex interaction between the physiological, personal and organisational resources available to the individual and the load placed upon them by their physical environment, work, and home life; symptoms occurring when the load on a person exceeded their resources to cope. This was a dynamic rather than static view, where resources and load both varied with time, and, where it would be difficult to predict outcomes from single 'causes'.

The view had several important implications for the methodology. Firstly, as people could have their load partially relieved by 'alleviators', which might include, for example, the visual quality of a workspace, the support provided by a supervisor or organisation, leisure and sport activities, it was important that the survey questionnaire covered a comprehensive range of alleviators. Secondly, as resources and load were constantly in flux within a dynamic built and organisational environment some gross effects of a building or its services might be discernible at the level of the whole building population but others might only be recognisable at the level of the building segment or individual person. To isolate these effects it was necessary to be able to analyse the data at varying levels of resolution, from the eight buildings level to that of the individual workstation.

Responding to the project's general aims a methodology was developed to :-
- be compatible with previous studies so that the results and conclusions could be compared;
- reflect the diverse causes of symptoms suggested by the literature by being multidimensional and multidisciplinery in its appraisals;
- address these issues, where possible, by means of existing and trusted methods of data collection and analysis;
- be capable of detecting spatial variations in symptom reporting within buildings and be capable of determining whether or not such variations were the result of specific spatial or organisational factors;
- sensitive to time variations in system performance, occupancy, or external weather;
- be sufficiently standardised to operate as successive self-contained building case studies and as a unified cross-buildings study.

A full description of the methodology is presented in the project's technical report, so only the key events in each building case study are presented here :
- An initial inspection of the services was made to determine whether the design of the HVAC system represented current good practice and whether in its operation it was free from obvious major problems.
- A formal written study proposal and time schedule was presented to the building owner or occupier prior to monitoring.
- An eight page self-completion questionnaire was distributed to every worker with a desk in the building. Questions gathered information on each respondent's health and sick leave, leisure and sporting activities, travel to work, job and organisational characteristics, degree of coping, life events within and outside work, and workspace.
- A whole building investigation of space use was performed to examine, for example, whether or not spatial integration-segregation influenced health reporting and associated behaviour. Summary spatial statistics



The general flow of events in a study of an individual building.

The spatial distribution of Occupant characteristics represented using a Geographical Information System (GIS).

for each individual were attached to database containing their questionnaire responses.

- Depending on the size and nature of the building air temperature was monitored for as long as 12 weeks in up to 20 locations throughout the building.
- Questionnaire responses within each building were exported from the survey database into a Geographical Information System (GIS) in order to determine whether there were spatial clusters of people who shared a common health characteristics. Where such clusters were identified a two week diary study was undertaken in conjunction with a focused examination of the HVAC services, more detailed longitudinal monitoring of the thermal environment, air quality, dust and pollutants, and a one-off investigation of the pattern of air movement. A series of summary statistics describing the environment occupied by each individual within a cluster were attached to the existing database containing questionnaire responses, together with similar statistics for each individual who worked within the domain of one of the long term temperature recording loggers.
- During an 'alternate season' study air temperature was measured for a one week period in a representative subset of the long term monitoring locations.
- Many of the results of the study could only emerge when the full dataset became available. Despite this, individual owners were eager to have an indication of their building's performance in advance of the final reporting stage. To satisfy this requirement oral presentations and written reports were given to each building owner as the study of their building was completed.
- Although a limited understanding could be achieved by examining individual buildings and the differences that occurred between various areas within a building, many of the most interesting comparisons could only be made after the eight building studies had been completed. This occurred during the final cross-buildings analysis and reporting stage.

Sample

Data was collected from nine buildings, of which eight were included in the full study. The eight buildings included eleven different organisations, four of which were private sector companies, three local authorities, three

Building	Organisational activity	date constructed or refurbished	Building depth	Max number of floors	No of floors investigated	Tot area of floors investigated (m2)	Office area investigated (m2)	Layout type	Level of spatial complexity	Degree of workstation enclosure	Office area/employee (m2)	% occupancy
1	Local authority	1974	Deep	4	4	8340	6684	Bürolandschaft	Medium	Medium	12	58
2	Financial services	1991	Deep	3	3	20531	10311	Open plan	Integrated	Low	15	58
3	Local authority	1991	Shallow	3	3	2852	2507	Mixed open & cellular	Medium	Medium	11	56
4	Government	1970	Shallow	23	10	7058	5367	Cellular	Segregated	High	20	64
5	-	-	-	-	-	-	-	-	-	-	-	-
6	Government	1988	Shallow	5	5	6062	4749	Mixed open & cellular	Medium	Medium	18	53
7	Tele-sales	1990	Medium	5	3	5118	3624	Open plan	Integrated	Low	12	79
8	Government	1962	Shallow	10	7	14117	12841	Cellular	Medium	High	21	N/A
9	Commercial	1992	Medium	3	3	5424	3084	Mixed open & cellular	Integrated	Low	11	28

Summary description of the buildings studied

	N
Population of the 9 Buildings	3285
Completed questionnaires	2191
Overall response rate	66.7
Gender	
Male	952
Female	1228
Unspecified	11
% of sample who were female	56.0
Job category	
Managerial	370
Clerical	587
Higher clerical	85
Professional & Executive	322
Technical	167
Administrative	223
Other	201
Tele-sales	124
Unspecified	112
Total	2191
Age	
Age 16 - 19	55
Age 20 - 29	666
Age 30 - 39	584
Age 40 - 49	490
Age 50 - 65	325
Unspecified	71
Total	2191
Smoking behaviour	
Smoker	383
Non-smoker	1792
Unspecified	16
% of sample who smoked	17.5
Pre-diagnosed as 'allergic'	
Previously diagnosed	524
Not previously diagnosed	1645
Unspecified	22
% of sample pre-diagnosed	23.9

Occupant characteristics for the eleven monitored organisations in nine buildings

	System type							Level of Control		
Building	Variable Air Volume	VAV/Constant Air Volume	Fan Coil	Perimiter Induction	Mechanical ventilation & cooling	Chilling	Humidification	Control near workstations	Zone control	BEMS control
1		•				•		•	•	
2					•	•			•	•
3			•			•			•	
4				•		•	•		•	
5	•					•		•	•	
6		•				•		•		
7			•			•		•		
8				•		•		•		
9			•			•	•	•	•	•

HVAC system characteristics and the type of environmental control applicable to each building.

central government departments or agencies and one trade union. One of the buildings (Building 5) was dropped from the study after the completed questionnaires had been collected. Occupants of that building agreed that their questionnaire responses could be included in the study. Although there were variations between the buildings an average response rate of 66.7% was achieved across the survey. Of the 2191 people who completed a full questionnaire 56% were female, 18% were smokers and 24% had been diagnosed at some time by a doctor as suffering from an allergy.

In selecting the case studies nearly one hundred buildings, the majority of which were visited, were considered for investigation. In reaching their judgment the research team and the supervising management committee applied the selection criteria listed below.

- The HVAC system : to avoid telling the industry what it already knew and to better understand the problems experienced in the general building stock the study, with two conscious exceptions, intentionally avoided investigating buildings where the HVAC services were more than five years old, or where there were obvious design faults or known system problems that may have impacted on occupant health.
- New buildings : because of their complexity or because of communication difficulties the services in buildings can take some time to settle into their normal operating pattern. To limit the effect of commissioning problems, operator inexperience or relocation buildings were only selected where organisation had occupied the building for at least a year and where the HVAC services were more than a year old. At another level the analysis was controlled, on occasions, for the time that had elapsed since the respondent had moved to their current workstation.
- Healthy and unhealthy buildings : initially the study called for an investigation of equal numbers of healthy and unhealthy buildings. Whilst this intention was laudable, it raised a problem of how to reliably determine in advance of an investigation whether or not the occupants of a building were healthy. To avoid the difficulty it was decided not to rigorously identify buildings in terms of the health of their occupants before the study but instead to select buildings upon a range of criteria amongst which was a personal judgement by somebody outside the study that the building population was healthy or not. The final and more reliable judgement being left to the analysis stage, when buildings could be distinguished according to how the occupants had responded to a range of health measures.
- Organisational conflict : buildings occupied by organisations that were in dispute with their workforce were rejected. In all cases representatives of both the employer and employees were approached to obtain their agreement to the study. In nearly every instance, such representatives were also invited to the feedback session to building owners at the end of monitoring.

Health indices

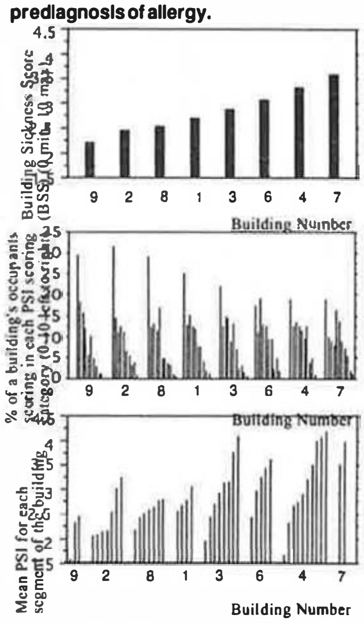
The central concern of the study were those health symptoms generally associated with the phenomenon Sick Building Syndrome (SBS). Other building related illnesses such as legionnaires disease and humidifier

	BSS	Health 1 *	Health 2 *	Health 3 *	Days Sick
Building 1	2.7	100	99	100	4.6
Building 2	2.4	99	99	99	4.3
Building 3	2.9	100	100	100	6.7
Building 4	3.2	103	100	101	5.8
Building 5	2.5	98	102	101	7.5
Building 6	3.1	102	101	101	8.7
Building 7	3.6	104	103	100	11.0
Building 8	2.5	99	100	100	6.1
Building 9	2.2	98	100	100	4.3
Whole study	2.7	100	100	100	6.1
p	.000	.000	.004	.593	.000
n	1677	1677	1677	1677	2039
Males (n = 751)	2.3	99	98	100	4.6
Females (n = 925)	3.1	101	102	100	7.3
p	.000	.000	.000	.105	.000
Smokers (n = 287)	3.1	101	101	100	7.9
Non-smokers (n = 1386)	2.7	100	100	100	5.7
p	.003	.024	.015	.338	.001
Prediagnosed (n = 386)	3.3	101	101	103	7.5
Notdiagnosed (n = 1279)	2.6	100	100	99	5.6
p	.000	.008	.003	.000	.002
Age (r)	*-.06*	*-.09*	-.04	.06	.00

* Standardised factor score, with a mean of 100 and a standard deviation of 10.

r Italicised correlations are significant at .05

Variations in the occurrence of individual symptoms, Building Sickness Scores (BSS), the three health factors, and sick leave by building, gender, smoking behaviour and prediagnosis of allergy.



Factors and symptoms	Rotated factor loading	Eigen Value	% Variance	Cumulative %	Communality
Factor 1		3.6	36.1	36.1	
Runny nose	.8041				.6494
Blocked nose	.7714				.6280
Flu like symptoms	.6416				.5246
Lethargy	.4752				.4308
Dry throat	.4641				.4654
Headaches	.4230				.3906
Factor 2		1.2	12.1	48.2	
Dry eyes	.8594				.7479
Itching eyes	.8250				.7048
Dry throat	.4799				
Headaches	.4528				
Lethargy	.4356				
Factor 3		1.2	11.7	59.9	
Tight chest	.8492				.7393
Difficulty in breathing	.8108				.7092

Three independent 'health' factors distinguished by principal components analysis.

fever were not specifically addressed.

The principal symptoms encompassed by the study included :-

- dryness of the eyes
- blocked or stuffy nose
- dry throat
- headache
- difficulty in breathing
- itching or watering of the eyes
- runny nose
- lethargy and/or tiredness
- flu-like illness
- tightness of the chest

In contrast to some earlier studies a secondary set of symptoms were included in the list so as to reduce unnecessarily focusing (or biasing) respondents' attention towards the symptoms of main interest. The secondary list was drawn from symptoms that had been peripherally associated with building related factors (contact lens problems, skin rash) and symptoms that were either general to the population (backache) or unlikely to be related to any great extent to building related factors (tinnitus).

In order to compare occupant health between buildings two related indices were developed, from the general symptom set, by previous research[2]. The first of these, aggregates an occupant's responses with respect to each of the ten SBS symptoms into a single measure, known as the Person Symptom Index (PSI). Given that there are 10 symptoms in the index a person's PSI score can vary anywhere between a minimum of 0 and a maximum of 10. The mean of all the building occupants' PSIs then constitutes the second index, the Building Sickness Score (BSS) for the building. As with the PSI a building's BSS can very between a theoretical minimum of 0 and maximum of 10. A BSS of 3.0 is usually considered to denote the threshold between health and illhealth.

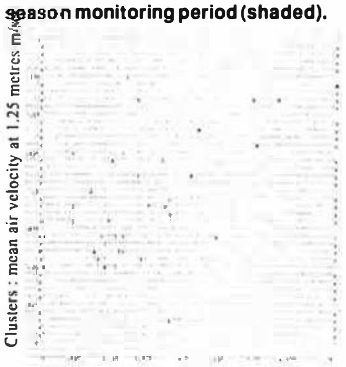
Verifying the findings from the GIS procedure mentioned above, statistical analysis across buildings, and between segments, zones or floors within the same building, showed that there was at least as much variation in symptom reporting within buildings as there was between buildings. This is demonstrated by the three adjacent graphs. Examination of the middle graph shows that approximately 70% of the respondents in each building complained of at least one symptom.

As the PSI does not represent a coherent medical condition, a principal components analysis[3] of its ten constituent symptoms was performed to determine whether the symptoms grouped in such a manner as to indicate a known condition. This analysis distinguished three factors (Health1, Health2 and Health3), which may be described as a "nasal" factor (chronic nonallergic vasomotor rhinitis[4]), an "eye irritation" factor, and a "chest" factor. Individual factors scores were generated for every respondent, which were then used in place of the PSI in many analyses.

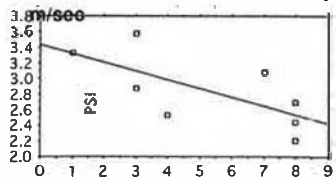
In addition to recording the symptoms from each participating occupant and calculating their PSI and related indices, self-reported sickness absence was recorded for each individual.

Building	Summer: Air temperature : Mean ºC	Summer: Air temperature : Standard Deviation ºC	Summer: Relative humidity	Summer: Carbon Dioxide ppm	Winter: Air temperature : Mean ºC	Winter: Air temperature : Standard Deviation ºC	Winter: Relative humidity	Winter: Carbon Dioxide ppm
1	22.4	0.90	48	479	22.8	0.96	30	479
2	22.8	0.51	45	385	23.1	0.77	31	505
3	23.2	1.02	50	554	22.2	1.29	35	612
4	23.0	1.40	46	488	23.0	1.18	38	547
5	-	-	-	-	-	-	-	-
6	22.6	0.76	44	578	22.1	1.10	30	644
7	23.4	0.95	48	519	23.0	0.97	25	596
8	23.1	1.43	41	494	23.4	1.61	33	526
9	22.9	1.15	49	491	-	-	-	-

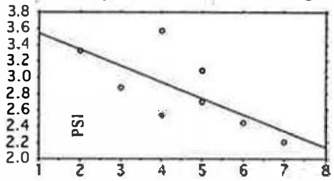
Whole building average temperatures and carbon dioxide levels in the main monitoring period and the alternate season monitoring period (shaded).



Clusters : mean inlet air velocity



Quality of Maintenance rating



System Performance Index rating

Building	Carbon dioxide ppm	Mean Carbon monoxide ppm	Mean TVOC ppm	Mean Formaldehyde ppm	Dust mites/gm	Respirable dust mg/m3	Max particle size micron
1	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-
3	677	1.02	0.51	0.06	4.00	-	-
4	533	0.24	2.62	0.08	1.00	0.02	34
5	-	-	-	-	-	-	-
6	789	1.64	2.42	0.12	1.67	0.02	125
7	498	0.67	0.70	0.06	0.00	0.05	28
8	556	0.25	0.53	0.06	2.50	0.04	39
9	543	0.20	2.14	0.06	0.50	0.02	50

Whole building mean values for gaseous pollutants and dust.

The environment within the buildings

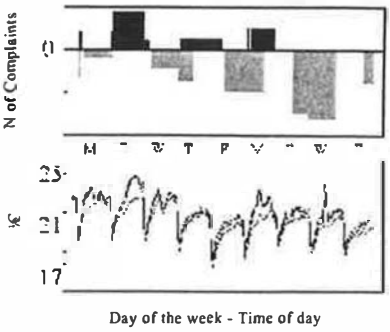
Air temperatures in most of the buildings were slightly high in comparison to CIBSE recommendations, with the mean air temperature in many workspaces exceeding 23½C. There was little difference between summer and winter conditions.

After controlling for the time a person had been located at a their workstation, occupant satisfaction with the thermal environment and their ability to control temperatures was one of the strongest correlates of both the nasal ($r = -.1956$, $p<.01$, $n = 857$) and eye factors ($r = -2634$, $p<.01$, $n = 857$), with greater dissatisfaction and more frequent reports of uncontrollable underheating (Health1 $r = -.1277$, $p<.01$, Health2 $r = -.1059$, $p<.01$, $n = 732$) and overheating (Health1 $r = -.2079$, $p<.01$, Health2 $r = -.2276$, $p<.01$, $n = 732$) being associated with more frequent symptom reporting. Despite this finding, only a very limited relationship was found between these factors (based upon the reporting of symptoms over the preceding 12 months) and temperature measurements taken in the weeks following questionnaire completion. In general, higher minimum temperatures were associated with lower nasal factor scores ($r = -.1646$, $p<.01$) and greater temperature variation with less frequent eye irritation.

Mean relative humidity values were similar across all the buildings with winter values being 15-20% below those of summer (only Buildings 4 and 9 had humidification). Carbon dioxide levels were similar in summer and winter, with average levels in all cases not exceeding 644 ppm. This indicates satisfactory fresh air ventilation (recommended values are below 1000 ppm for offices). Mean air speed varied across all the offices, ranging from 0.05 m/s and 0.175 m/s. 0.05m/s could be considered low possibly resulting in stuffiness whilst 0.175 m/s could be considered to constitute a draught in winter. The healthier environments appeared to be those with higher air movement. Air velocity at 1.25 m in workspaces correlated reasonably well with diffuser inlet air velocity.

Measured pollutants levels were generally low in comparison to the best available standards set by the Canadian and Swedish authorities. Carbon monoxide levels were consistently low in all the buildings when compared to the recommended maximum long term exposure of 50 ppm. VOC's and formaldehyde were more borderline in comparison with the recommended maximum values of 0.3 to 5.0 ppm for VOCs and 0.08 to 0.l ppm for Formaldehyde. Dust mite levels were very low when compared to the typical level (500 mites/grm) found in homes. Respirable dust levels were also low in contrast to recommended maximum values of 0.l mg/m3.

A routine assessment procedure was adopted for surveying the air conditioning system in each office . This was based on visual inspection together with interviews with the buildings operation staff. A professional judgement with respect to each building's maintenance and system performance was made according to a standard index developed in the study (see main report). The index values correlate reasonably well with the BSS. Previous studies[2] have indicated similar relationships between sickness reporting and the operation and maintenance of the HVAC system.



Reports of over/underheating during the diary study by day of the week with corresponding air temperatures measurements from the respondent's workspace.

Cluster	Mean Temperature ÞC at 2.0 m	Temperature STDDEV ÞC at 2.0 m	Mean Temperature ÞC at 1.5 m	Temperature STDDEV ÞC at 1.5 m	Mean Temperature ÞC at 0.3 m	Temperature STDDEV ÞC at 0.3 m
7.2	-	-	-	-	-	-
7.3	25.0	0.6	24.2	0.6	22.8	0.7
7.4	23.4	0.6	22.7	0.6	21.7	0.5
7.5	24.1	0.8	23.3	0.8	22.8	0.7
7.6	22.7	0.9	22.1	0.8	21.3	0.9
7.8	23.6	0.8	23.1	0.6	22.5	0.6
Mean	23.7	0.7	23.0	0.7	22.1	0.7
9.21	22.2	0.3	22.4	0.4	22.3	0.4
9.22	22.6	0.4	22.1	0.5	22.0	0.5
9.32	22.2	0.7	22.0	0.6	-	-
Mean	22.3	0.5	22.2	0.5	22.2	0.4

Cluster	MRT Mean ÞC	MRT STDDEV ÞC	Air velocity at 1.25 m	Mean Inlet air velocity	Inlet air velocity standard deviation	Room C02 ppm
7.2	-	-	0.05	1.26	0.42	486
7.3	24.0	0.6	0.07	1.03	0.25	530
7.4	22.8	0.6	0.08	1.10	0.91	502
7.5	23.1	0.8	0.07	1.37	0.38	483
7.6	22.8	0.8	0.07	1.24	0.51	488
7.8	23.3	0.7	0.06	1.33	0.47	498
Mean	23.1	0.7	0.07	1.21	0.49	496
9.21	23.1	0.4	0.16	3.65	1.89	516
9.22	21.9	0.5	0.12	2.06	0.53	586
9.32	22.3	0.6	0.16	1.63	0.56	526
Mean	22.5	0.5	0.15	2.50	1.06	537

Environmental conditions at 'cluster' locations in Building 7 and Building 9.

In accordance with the procedure detailed above, each occupant within a cluster area was asked to keep a diary during a two week period of focused physical monitoring. The diaries recorded the occupant's symptoms and perceptions of discomfort. Little agreement was found in the chronology or type of symptoms reported by members of the same cluster. Furthermore, no relationship was discerned between symptom reporting and concomitant physical conditions. In other words symptom reporting appeared to be a random phenomena, or mediated by factors beyond the immediate physical environment.

Spatial relations

The investigation found that higher levels of PSI, and Health Factors 1 and 2 were associated with greater spatial complexity, segregation and enclosure of the workstation. It is likely that these results reflect the historical trends in building and layout forms in the UK over the past 30 years, where more unhealthy buildings tend to be older, and to have cellular and complex layouts. These spatial characteristics coincided with poor HVAC performance and low quality of maintenance ratings, as assessed by the services investigation. These were likely to be the underlying reason for ill health rather than any inherent spatial characteristics. However, there were indications that high levels of segregation adversely affected communication networks between people resident on different floors. This was likely to affect organisational performance and well being.

Determinants of health

A wide range of descriptive, inferential and regression analyses were performed on the extensive dataset generated by the questionnaire survey, spatial observations and physical monitoring. These are reported in full in the project's technical report. A specimen analysis of covariance, examining the healthiest and unhealthiest buildings (Building 7 and Building 9), is reported here to portray the study's general findings.

This analysis involved the following steps :-

- visual comparison of the means and standard deviations for each of the potential explanatory variables (chosen chiefly from factors derived by principal components analysis of the various sections of the questionnaire data), looking for those instances where the two groups of occupants differed most;
- an examination of the correlations between the potential explanatory variables and the selected health factor, to determine which of the independent variables was the highest correlate of the health factor across the two buildings;
- then, by examining the products of the first two steps in conjunction with one another, identifying potential covariates which might both explain the occurrence of symptoms in this specific instance and, therefore, the difference between the two buildings;
- an analysis of covariance using the covariates selected by the first three steps to determine whether, whilst controlling for the known influence of occupant characteristics such as gender and smoking behaviour, the covariates removed the previously noted difference between the buildings. In other words, to establish whether after controlling for other factors the covariates explained the difference between the two buildings;
- having identified potential explanations for why the contrasting buildings differed significantly, available objective measurements were then analysed to see whether they supported the conclusions based upon an analysis of subjective responses.

Using this procedure, most of the difference in Health1 (nasal factor) scores between the two buildings may be explained in terms of the workspace thermal environment, the workspace visual environment and job factors. That is, the occupants of less healthy building (7) :-

- reported a greater frequency of overheating problems throughout the year,
- scored their workspace visual environments as less satisfactory, and
- were less satisfied with their working environment and their jobs as duller, more repetitive and less challenging, in comparison to the occupants of Building 9.

Examination of the physical measurements from the two buildings suggests that Building 7 is less thermally comfortable than Building 9, in that the former is characterised by slightly higher temperatures, and lower air velocities at seated level (the difference in relative humidity was most likely due to the contrasting seasons during which the measurements were taken).

Further analysis of the questionnaires from the two buildings indicated that job satisfaction varied significantly between the two samples with the employees in Building 9 being more satisfied than those of Building 7. Regression analysis of the responses from Building 7's employees suggested that a very limited set of job characteristics mighty be responsible for the measured level of satisfaction. Some 63% ($r^2 = .630$) of the variance in the respondents' job satisfaction assessments were explained by just three aspects of the job. These were :-

- "I feel very fulfilled by the work that I do" (Beta .6290),
- "My work is challenging and stimulating" (Beta .1416), and,
- "I feel I belong in this organisation and would be very sorry to leave it" (Beta .1365).

In summary, there was a lower level of job satisfaction amongst the occupants of Building 7, related both to the nature of the work and the character of the organisation. And it is this dissatisfaction, possibly in conjunction with the differences in thermal conditions, which may be responsible for the observed difference in the nasal factor scores between Buildings 7 and 9. However, some of the difference between the buildings, particularly that related to job characteristics, may reflect variations in the constitution of the two samples rather than real differences between the organisations or buildings. This is because the sample in Building 7 was largely drawn from one group, telesales agents, whilst that in Building 9 was more evenly represented by people from all job categories. It is important to emphasise that the method used can only give an indication as to the processes responsible for the symptoms in this case, causality must not be automatically inferred.

Conclusions

Health, work and the environment

- **Health factors** : principal components analysis of the 10 constituent symptoms of the well established measure of 'building related' illness in office workers, the Person Symptom Index (PSI), suggests there is no single phenomenon that merits the term Sick Building Syndrome. The analysis distinguished three independent factors, termed health factors, amongst the 10 PSI symptoms : a nasal factor (36% of the variance in the ten constituent symptoms of the PSI), an eye irritation factor (12%), and a chest-breathing difficulty factor (12%).
- **Nonallergic rhinitis** : the nasal factor identified in this study is more like chronic nonallergic vasomotor rhinitis, which is experienced in the absence of eye symptoms and which Stites and Terr describe as : "a common disorder of unknown cause ... symptoms occur year-round and are generally worse in cold weather or in dry climates ... the disease is more common among women ... allergy skin tests are negative or unrelated to the symptoms".
- **Symptom reporting** : although perceived thermal conditions are frequently implicated in symptom reporting, the issues which promote symptom reporting can vary from building to building and from location to location within a building. A building where the environment might suggest a high symptom count can in fact house occupants with low counts. The reason for this may lie in the character of occupants' jobs and the organisation they work for. At worst the built and working environments studied were only contributing to the symptoms reported. Such factors can not be cited as the sole determinant of the symptoms.
- **Groups prone to symptoms** : certain groups of people were more prone to symptoms or took more time off work for sickness reasons. For instance, females were significantly unhealthier than males according to both the first and second health factors but not the third. A similar pattern of differences was discernible between smokers and nonsmokers. People who had been medically diagnosed at some time in their life as suffering from an allergy were also more prone to higher scores on the three factors. Females,

smokers and previously diagnosed people all reported having taken significantly more sick leave in the past year than their counterparts.

- **The nature of the job** : comparing contrasting buildings according to symptom counts suggests that higher levels of job satisfaction, job fulfilment, and sense of belonging to the organisation occur in those buildings where lower symptom counts are recorded. Regression analysis identified three work characteristics as being common amongst people with high nasal factor scores. These were : the performance of dull and repetitive jobs, feelings of social isolation and unhappiness at work, and the performance of mainly self-contained tasks independent of other people.
- **The role of buildings** : although at least 70% of the occupants in the study complained of at least one symptom detailed statistical analysis could only attribute a maximum of 20% of the variation in symptom reporting to the physical or organisational environments within the buildings or personal characteristics of the respondents.
- **The physical environment** : the measurements indicated only a limited relationship between the thermal environment and symptoms. The general findings from the physical measurements indicated relatively high internal air temperatures and considerable variations in internal air velocities which could be related to the air supply characteristics. Measured levels of pollutants, dust and dust mites were in most instances were within or close to the maximum recommended values of the most stringent of international standards. It is likely, therefore, that the physical environment within air conditioned offices only plays a contributory role in symptom generation.
- **Interrelationships** : a number of complex interrelationships emerged between the environment and, the occupants' sense of control, internal spatial design factors, the relationship to the outside physical world and the nature of the work engaged in. Such interrelationships were clearly present but will need further intervention studies to address their complex nature.

HVAC

- **Air conditioned offices** : six of the nine air conditioned office buildings studied had Building Sickness Scores (BSS - the mean PSI score for a building) within the 'healthy' range according to the criteria established by Wilson and Hedge's[2] survey. Although the current study specifically rejected buildings with HVAC system design faults or gross operational problems it did not exclude buildings that were reported to be "sick". The range of Building Sickness Scores therefore suggests there is nothing inherently unhealthy about air conditioned buildings.
- **Age of the system** : where a system was properly maintained and controlled its age was not a major determinant of occupant health, although poor maintenance of older systems was implicated. Workspaces that conform to CIBSE or other widely accepted guidelines with respect to temperatures and air movement should not, in the absence of aggravating work related factors or extreme pollutant levels, give rise to high symptom counts. In this context, problematic environments tend to be those where the system is unable to deliver the necessary conditions due to advanced age affecting controllability or inapprpropriate operation. In this study some twenty year old systems were found to be delivering reasonably healthy and comfortable environments with the diligent and expert help of a good facilities team.
- **System complexity** : simple HVAC systems (mechanical ventilation with cooling) with effective but simple control (on a large zone basis), in large open plan areas do not appear to have adverse effects upon health reporting. Simple, zone by zone, control systems in open plan buildings can be just as effective as sophisticated BEM system control.
- **System control and occupant control** : in a well operated and maintained system and building, lack of control by individuals over their thermal environment was not a factor in symptom reporting. However, poorly controlled systems that resulted in wide variations in temperature were implicated in symptom reporting. Therefore, it would appear that where the central control is sufficient to maintain conditions in open plan areas the perceived lack of control by individuals does not necessarily lead to symptom reporting.
- **The facilities team** : the facilities teams that managed the healthiest buildings in this study were characterised by their knowledge of the systems and buildings they operated, their personal motivation, and the degree of support given them by the organisation they served. These teams managed their

systems in a pro-active manner with planned maintenance scheduled into the general operation of the Building Management System. A good facilities team listens to, but not necessarily indulges, their building and its occupants.

- **Informed intervention** : decisions that lead to intervention in the system must be based on full knowledge of the issue or problem, and an open but critical view of occupant complaints. Maintenance engineers should monitor the performance of the system prior to making alterations and continue to monitor the situation following the intervention, to test its effectiveness.

Space

- **Spatial simplicity** : for good communication networks offices should be designed so as to be spatially simple and integrated. This can be achieved by having few rather than many floors, through simple internal layouts, direct connections between workplaces and circulation, and direct connections between different parts of a complex of buildings.
- **Spatial design** : the degree of workstation enclosure is unimportant to communication. Both open and cellular plans can be both interactive or non-interactive, according to the overall characteristics of the layout. Cellular configurations are therefore recommended where the task involves both communication with others and individual quiet work.
- **Office layout** : there are some indications that in future office layouts are likely to become more cellular and more subject to frequent change. HVAC systems should be therefore be designed to cope with high levels of cellularisation, frequent changes in the location of full height walls, and the ability to give individual control within cellular spaces.

Summary Guidelines

- **CIBSE guidelines** : there is no evidence to suggest that using CIBSE guidelines to design an air conditioned building will result in an unhealthy environment. Problems generally arise through deficiencies in detailed spatial design and inadequate knowledge of the way the building will be used and operated over time in relation to functional changes.
- **Responding to the environmental characteristics of individual areas of a building** : increased importance should be given to the environmental design of individual spaces and areas within buildings.
- **Design for control** : particular attention should be given to ensuring that environmental conditions can be maintained within CIBSE criteria on a daily and seasonal basis. In particular air temperature and air speed should be carefully controlled.
- **Responding to spatial arrangements** : the design of the environment and HVAC system should account for spatial arrangement and furnishing.
- **Flexible design** : a design should ensure flexibility for local control of environments in response to changes in spatial demands and changing office layouts.
- **HVAC O&M** : systems should facilitate easily manageable operational and maintenance procedures that match the proficiency and skill levels of available building services personnel.

References

1. Raw G Slater A Tong D and Lush D. Sick Building Syndrome : a Review of the Evidence on Causes and Solutions. The Building Research Establishment. 1992.
2. Wilson S and Hedge A. The Office Environment Survey : A Study of Building Sickness. London : Building Use Studies Limited 1987.
3. Wallace L A Nelson C J and Dunteman G. Workplace characteristics associated with health and comfort concerns in three office buildings in Washington D.C. Proceedings IAQ '91 - Healthy Buildings, Washington D.C. Atlanta : ASHRAE. 1991.
4. Daniel P Stites and Abba I Terr. Basic and clinical immunology. 7th edition. Connecticut : Appleton and Lange 1991.

Project bibliography

P J Jones, N Vaughan, P O'Sullivan, W Hillier and T Grajewski, *A Methodology for Developing New Guidelines for the Design and Operation of Healthy Office Environments*, Healthy Buildings Conference, Budapest, August 1994.

P J Jones, N Vaughan, T Grajewski and H Jenkins, Internal Conditions and the Response of Office Workers, Workplace Comfort Forum, RIBA 22 and 23 March 1995.

P J Jones, N Vaughan, P E O'Sullivan, W Hillier and T Grajewski, Case Studies of Health in Offices in the UK, Indoor Air Quality in Asia, Proceedings of the International Conference held in Beijing, China, 18-20 October 1994, ISBN 3-906470-04-0, pp 141-149.

Jones P J Vaughan N D O'Sullivan P E, W Hillier, T Grajewski. An *integrated methodology for investigating occupant health in air conditioned offices.* Proceedings of the First International Conference on Buildings and the Environment, CIB. 'Indoor' Session Paper 6, Garston : BRE, 1994, 7 pages.

Jones P J Vaughan N D Jenkins H J O'Sullivan P E Hillier W Grajewski T and Young A. *Health in the Workplace : a review of a contemporary investigation.* The 2nd Indoor Air Quality Conference. Cambridge : Mid Career College, CIBSE, 1994, 10-23.

N Vaughan, P J Jones T Grajewski W Hillier H G Jenkins P E O'Sullivan and A Young, *New Guidelines for the Design of Healthy Office Environments - Four Buildings Study* Peer Review Seminar, UCL London, March 1994.

N Vaughan, P J Jones T Grajewski W Hillier H G Jenkins P E O'Sullivan and A Young *New Guidelines for the Design of Healthy Office Environments - Guide to Procedures,* Peer Review Seminar, UCL London, March 1994.

P Jones, *Office Environments and Sick Building Syndrome*, invited research lecture at the Martin Centre for Architectural and Urban Studies, University of Cambridge, November 1994.

The impact of feedback on domestic energy consumption

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Summary

Over the past two years a sample of properties in Bath have been studied in order to establish the effect of providing gas and electricity consumers with various kinds of feedback on their energy consumption. Information on the physical characteristics of the properties was collected, along with socio-economic and attitudinal data from the residents. Energy consumption was monitored over a winter and six different kinds of feedback were introduced in order to establish which was the most effective. The results indicate that feedback delivered via a computer led to the most significant reductions in energy consumption and this finding is being investigated in the next stage of the project which will be looking at the implications of delivering feedback using a 'smart' meter.

Introduction

Whilst the public has become increasingly environmentally conscious in recent years, the extent to which people have changed their lifestyles in response to such concerns is often limited. With regards to energy conservation, the link with environmental problems is not always obvious and the subsequent mismatch between concern and action may arise in developed countries where as energy has got cheaper and less intrusive in our lives (few Westerners have direct contact with a primary fuel or energy source) it has become, in effect, invisible. Clearly, this poses problems for anybody involved in the promotion of energy conservation and raises questions of how to make the energy used in our homes and workplaces more visible. It is a problem which also affects energy suppliers as they have a vested interest in controlling demand in order to minimise additional capital expenditure on power generation.

Research at Bath University has sought to establish how this 'invisibility' of domestic energy use could be counteracted by the use of different forms of feedback; feedback which, in terms of policy relevance, could feasibly be delivered as part of a government energy efficiency campaign.

The project

Using local census data, participants were selected from areas of mixed housing types and tenure all within five storey Georgian terraced buildings. 140 households took part with social and attitude data collected via interviews and building and appliance data collected through detailed surveys. The sample was then divided into 7 feedback conditions with an even spread of the variables that previous research had suggested were relevant in terms of energy use differences: tenure, number of occupants and age of occupants.

Because the presence of certain structural features within a home will have an impact on the energy efficiency of a property, regardless of the behaviour of the occupants, information gathered from the home surveys was used to give each household a structural energy efficiency rating. A behavioural efficiency rating, based on respondents' existing conservation activities, was also constructed as a household's behaviour can do much to reduce energy use. This was an important procedure as any changes in consumption must be related to the potential for savings that exist in the first place.

All the gas and electricity meters of the participants were initially read during July 1995 to provide baseline consumption figures and then every month subsequently until April 1996.

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The dependent variable

To ascertain whether feedback had any impact on consumption patterns all participating households had to have their consumption over the period of the field study compared to the same time in the previous year, using figures provided by the appropriate utilities. All consumption was measured in KWhs as opposed to the unit figures used by the utilities in order that the dependent variable, the percentage change in total consumption, would be comparable for all households regardless of the fuels they used. The comparative figures were weather corrected using data from two local weather stations and the Meteorological Office. The total percentage difference (TOTPD) measure was therefore calculated as follows;

$$\text{TOTPD} = \frac{\text{field study consumption - historic consumption}}{\text{historic consumption}} \times 100$$

Feedback

All the feedback groups, apart from the control, received monthly feedback in the form of a letter containing their gas and electricity consumption along with additional customised. With the exception of the group 6, all the feedback was presented in a form that could be implemented as part of national policy at moderate cost, simply involving more regular fuel bills and additional printed information. The feedback was customised as follows:

Group 1 - Self-versus-Others Comparison
Received feedback informing them of their energy consumption in relation to an average figure for a similar other property.

Group 2 - Self-versus-Self Comparison
This group simply had their current months consumption presented alongside that for the same time last year, weather corrected.

Group 3 - Leaflets
At the start of the project, this group were provided with a full literature pack of currently available government produced energy advice leaflets and each month their consumption was represented in graph form.

Group 4 - Money
Received both KWh and equivalent monetary value consumption figures and were provided with an information sheet giving them the running costs of household appliances.

Group 5 - Environment
Were informed about the environmental impacts of their energy consumption alongside their monthly consumption.

Group 6 - Computers
Each member of this group received a personal computer for the duration of the project. The PCs contained 3 different programs: the first required the user to input periodic meter readings which were then converted to KWh consumption and plotted on a graph to enable a comparison with the previous year's consumption; the second contained a questionnaire on general aspects of energy saving in the home; the third contained information and advice on all aspects of energy saving which could be viewed by the occupants at their discretion.

Results

Tenure and structural energy efficiency

Initial analysis of the relationship between energy consumption prior to feedback and a variety of socio-economic variables found that the type of tenure related closely to the structural energy efficiency of homes. Local Authority properties had an average score virtually the same as the survey average. Mortgaged and owned properties shared a similar score distribution pattern: both had a large peak around the survey average followed by smaller peaks at the higher end of the scale (the most energy efficient) with the curve of those properties owned outright being slightly above that of the mortgaged properties. Clearly, home owners stand to gain in several ways when they invest in energy efficiency, not only in terms of improved comfort and fuel savings but also because the value of their property is likely to increase.

The Local Authority houses were typified by their absence from the lower efficiency properties, indicating not only that the Local Authority maintains its properties well with regards to their energy efficiency but perhaps also the greater likelihood of tenants in such properties qualifying for subsidised insulation and draught proofing programmes such as those run by Energy Advice Centres. Privately rented properties, on the other hand, were those most likely to be energy inefficient, a probable result of both the more transitory nature of private tenants, who were less likely to invest in energy efficiency measures, and landlords who might be loath to invest in measures involving them in additional capital outlay.

Consumption Changes

In order to assess what changes in consumption could be attributed to the introduction of feedback it was necessary to establish which factors, if any, related to household energy consumption before the research began. A multiple regression was performed using previous (historic) consumption as the dependent variable to ascertain whether income and demographic variables, identified by earlier research as important (Fahar & Fitzpatrick, 1989) were influential in this case. The analysis for the independent variables 'household income', 'age of respondents' and 'number in household' all proved significant and showed that 'mature' households with higher incomes and more occupants consumed more energy. A one way analysis of variance for all four tenure groups also produced statistically significant differences revealing those renting from the Local Authority to be the lowest consumers which, as already discussed, may relate to the relatively high energy efficiency of such properties, but is also likely to be a function of the low incomes typifying such households. No other variables had any influence on previous energy consumption.

These results contrast markedly with those produced when the dependent variable of the field study is analysed (the total percentage difference between previous consumption and consumption during the field study) as the variables found to relate to previous consumption levels, namely, income, age, number of occupants and tenure, did not relate to consumption levels post-feedback. However, the attitude variables (environmental beliefs and predicted personal behaviour), which were insignificant in terms of previous consumption, were found to relate to reductions in consumption. Respondents who had reduced their consumption were more likely to have pro-environmental attitudes and to have expressed a pro-active view with regards to their future conservation behaviour.

In terms of non-parametric analysis, that is concentrating on the direction of changes in consumption rather than the sizes of these changes, medium and high energy users were more likely to reduce their consumption than low energy users. When examining the performance of the various feedback groups (using a binomial test), the only significant difference was in the case of the computers. This group was notable not only for the percentage of households reducing, over 80% compared the other groups average of 55%, but also because they made bigger savings and the majority of them reduced their use of all fuels compared to one third or less of members in the other conditions.

Discussion and policy implications

The analysis reveals that the feedback across all groups, compared with the control conditions and environmental attitudes and behaviour, had a marginal statistically significant influence on the total percentage difference of energy consumed for the period of the study.

Environmental attitudes had no statistically significant effect on previous consumption but were related to the changes in consumption over the feedback period. On the other hand, whilst income and socio-demographic variables did relate to pre-feedback consumption levels they did not influence consumption over the feedback period. This suggests that favourable attitudes, feedback and raised consciousness brought about by taking part in the study all contributed to a change in behaviour across the board and not just for one particular kind of household.

There are three main policy implications raised by the study relating to behavioural potential (targeting), particularisation and visibility. Firstly, whilst many people have favourable environmental attitudes the connections between individual energy consumption and environmental problems are often not obvious. However, our results indicate that energy conservation information is more likely to be effective if it is targeted at people with favourable environmental attitudes. By association, therefore, an increase in public environmental awareness may increase public receptivity to calls for fuel efficiency.

Secondly, our survey sample made it clear that consumers want customised advice. General or vague leaflets, often with inappropriate information, appear not to be sufficient. The only feedback form in which the present study can place any confidence is information, some of it interactive, supplied by computer software. This leads to the third point about visibility, as the success of the computer feedback is seen to demonstrate the importance of making fuel consumption more visible to domestic consumers.

Future research

Smart meters

A new generation of smart, integrated or intelligent meters is currently transforming the relations between production and consumption interests in both the energy and water sectors (IEE, 1987 & 1990). The driving force behind the new generation of 'smart' utility meters is that the energy providers see them as a way of reducing the cost of manual meter reading while providing new ways of predicting, and even managing, demand. However, the same technology can also help in the quest for greater sustainability by helping consumers to use their energy more effectively.

Through a combination of microprocessor and communications technology these new meters can:

- Read consumption data continuously and transmit it to the energy provider.
- Hold multiple tariff charge bands which can be altered dynamically.
- Provide a direct channel of communication between the energy provider and the consumer which can operate in real-time.
- Provide the consumer with current and aggregated data on patterns of energy consumption.
- Control major appliances directly, switching them on and off at certain times or when particular tariffs are available.

The next stage of the project will link this new metering technology with the data collected from our previous study on the effect of different kinds of feedback in order to provide the specification for a complete new 'green' meter designed to help the consumer make the most appropriate choices about energy use. This system will utilise existing hardware and will concentrate on those issues which directly affect the consumer - what information should be made available and how should it be presented in order to have maximum impact? It will contain the following elements:

Meter
This will be a microprocessor controlled pulse meter with communications links to the energy supplier. The current standard for pulse output meters which records energy consumption every 30 seconds will be used. The communications links will be capable of transmitting real-time information on energy consumption to the supplier and tariff information to the consumer.

Energy Advisor
This is something which does not currently exist and is an expert system which interprets the information flows from the meter to the energy supplier. Using the consumption data, supplemented by information on comfort conditions within the property, it will build a profile of the lifestyle of the consumer and then test out different energy conservation strategies by providing advice. Using the response to this advice it will refine its lifestyle profile to get the most appropriate strategy for maximising energy conservation.

Display Interface
Although currently ignored in developing new engineering solutions to domestic metering this part of the system is vital. Subjective factors, such as the appearance of the computer, can have a fundamental effect on how it is used. In the proposed system it is likely that the display will not be located on the meter, or on any associated computer, but in a prominent position in the house, perhaps in the manner recommended by Duancey (1990) who argues that *'it is time for the household meter to come out of the closet and appear as a piece of attractive household eco-furniture'.* This raises a whole host of issues, such as; which room is most appropriate; how big should the display be; what should it look like; how should information be presented; what level of control should be offered from the display? These issues are not covered by public communication theories, which tend to focus on questions of content, but are the ones that this research will investigate in order to establish how feedback can be delivered most effectively.(Rice & Paisley, 1981)

A sample of 20 households will be chosen from residents in Bath, all occupying similar buildings. Using existing collaborative arrangements with South Western Electricity Board and British Gas, the meters in these properties will be replaced by pulse output meters and a new telephone line will be installed to simulate the communications links with the public utilities. The research team will then act as the service provider in parallel with the utility companies. The output from the two meters will be fed into a computer located in the property which will also be connected to data logging equipment in the house and to the research team via the telephone line. The display interface will be located in a prominent position in the house and, in the first instance at least, will comprise a colour touch screen of the kind found in notebook computers.

Using the results of the previous study, profiles of consumers will be developed which take account of their socio-economic status and their stage in the family cycle and relate these to their patterns of energy consumption. This will enable us to establish particular lifestyle profiles and thus target appropriate advice on suitable energy conservation strategies. The effectiveness of these strategies can then be monitored directly and adjusted where appropriate.

By replicating the different feedback types used in our previous study, but in this case delivered through the smart meters, we will be able to calibrate results about the most appropriate ways of delivering conservation strategies. The research team will then investigate the effects of the dependent variables under consideration - the design of the interface to the consumer and the manipulation of the tariff band information. Acting as the service provider with respect to the latter variable will allow us to explore questions about how well people respond to variable tariffs and quantify any savings made (Rosenfield, Bulleit & Peddie, 1986).

References

Bulleit, D.A. & Peddie, R.A., (1986) 'Smart Meters and Spot Pricing: Experiments and Potential', Technology and Society Magazine, Vol 5, No. 1, pp23-28.

Dauncey, G. (1990) 'The Role of New Metering Technologies in Combating the Greenhouse Effect', in IEE 1990, pp57-61.

Fahar, B., & Fitzpatrick, C., (1989) 'Effects of Feedback on Residential Electricity Consumption: a literature review', Solar Energy Research Institute, US Department of Energy.

Institution of Electrical Engineers (1987) Proceedings of 5th International Conference on Metering Apparatus and Tariffs for Electricity Supply, Conference Publication No. 277, London.

Institution of Electrical Engineers (1990), Proceedings of 6th International Conference on Metering Apparatus and Tariffs for Electricity Supply, Conference Publication No. 317, London.

Rice, R.E. & Paisley, W.J. (eds) (1981) 'Public Communication Campaigns', Sage.

Rosenfield, A.H., Bulleit, D.A. & Peddie, R.A., (1986) 'Smart Meters and Spot Pricing: Experiments and Potential', Technology and Society Magazine, Vol 5, No. 1, pp23-28.

A land-use, transport, and energy model of a medium-sized city

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Summary

A detailed empirical study is being undertaken of the land-use, building-stock, and transport pattern of the town of Swindon in Wiltshire. The aim is to explore the relationship between urban form and energy-use in a town of medium size. The economic functioning of the town is being simulated with the TRANUS land-use and transport model developed by T. de la Barra. TRANUS will be used to compare and evaluate a series of future planning policies directed towards increasing 'sustainability'. Three different 'scenarios' are currently being explored: 'containment and increased density', 'high-density dispersal', and 'low-density dispersal. Results for each of the 'scenarios' should be available shortly.

Introduction

This paper relates to an ongoing project, funded by the Engineering and Physical Sciences Research Council under its initiative on Cities and Sustainability. It is a collaborative project involving the Open University and the University of Manchester, along with two consultants in private practice, Peter Rickaby of Rickaby Thompson Associates in Milton Keynes, and Tomas de la Barra of the Venezuelan Company Modelistica. Funding is for a two-year period and we are now a little over half way through the project.

The aim of the work is to explore the relationship between urban form and energy-use by reference to a town of medium size. Swindon, which now has a population of around 125,000, was a small market town until the middle of the nineteenth century, when it became the site of engineering works for the Great Western railway. The railway industry continued to dominate the town until the 1920's. Since then employment has shifted into other areas, including the manufacture of cars and, more recently, financial services, electronics, and information technology. During the 1980's Swindon was reputedly Europe's fastest growing city. It was chosen for the present project because, for all the peculiarities of its history, it would still seem to be reasonably representative of a large class of towns of this order of size. The research team had also gathered a large amount of data on Swindon in an earlier project.

By concentrating on a single town, we have been able to build a very detailed model, embracing the building stock, land-use pattern, and transport system of the city and its hinterland. Two software tools have been used. The shapes of land parcels, the three-dimensional forms of buildings, and the geometry of the road network are all being represented on the SMALLWORLD GIS (Geographical Information System). The economic functioning of the town is being simulated with the TRANUS integrated land-use and transport model developed by de la Barra. TRANUS will be used to compare and evaluate a series of future planning policies directed towards increasing sustainability.

Sustainability and urban form

There is no doubting the importance of 'sustainability' in current planning debate. Since the Brundtland Report (World Commission, 1987), increasing numbers of studies and official reports have focussed on the role of the city in achieving sustainability. The influential Green Paper on the Urban Environment,

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published by the Commission of the European Communities in 1990, argued in favour of high densities as a way of achieving energy efficiency and improved quality of life. In the U.K. Government initiatives have resulted in a Strategy for sustainable development (1994) and the Planning Policy Guidance note P.P.G. 13 (Department of the Environment, 1994), both of which advocate similar measures to reduce the need to travel.

A striking feature of recent literature has been the emphasis placed on the physical form of the city . Both inside and outside Government, there has been widespread support for the view that the most sustainable solution is to check the outward expansion of our cities. New development, it is argued, should as far as possible be concentrated within existing urban boundaries. The 'compact city' is seen to provide the key to a reduction in travel distances and a shift to more energy-efficient modes of transport. This, in turn, will help to provide the necessary reduction in fuel consumption and in the levels of pollution.

It is by no means clear, however, that a policy of 'compaction' or 'densification' is the appropriate route to take. The term 'sustainability' is, as we know, often defined in such general terms that it is extremely difficult to translate such a global conception into specific planning aims at the scale of a single city (Breheny, 1994). But even if we narrow our definition to focus on energy consumed in transport, the evidence to support compaction remains fairly limited. The influential study by Newman and Kenworthy (1989) points clearly to the relationship between petrol consumption and urban density, with dispersed American cities, such as Houston and Phoenix in the U.S.A., having by far the highest consumption. But their data have been shown to be susceptible to more than one interpretation: according to Breheny a rise in fuel prices is likely to have a much stronger effect in the long run on energy-use than increases in urban density (1995, 1996). Moreover, any policy of compaction has to face the fact that it is running counter to the prevailing trend. In Britain, as in most western countries, population and jobs continue steadily to move outwards from the city.

In the present study we are using the TRANUS model to test the effectiveness of urban compaction against a series of other hypothetical planning 'scenarios'. Various kinds of dispersal will be examined as well as concentration. To make the project manageable, we have taken a pragmatic approach to the complex issue of sustainability, concentrating on a number of clearcut goals for urban planning. Amongst these are the lowered use of fossil fuels, through conservation measures in buildings, a reduction in the numbers and lengths of motorised journeys, and by shifting journeys from private to public modes, or better still to cycling and walking. Our emphasis is, therefore, primarily on energy conservation. But we intend to set any predicted fuel savings against their cost, both financial and in terms of reduced accessibility. We will take account of certain aspects of social equity in access to transport. We also hope to assess in more qualitative terms the effects on the built environment of changes in density and the mixture of activities.

The TRANUS model

TRANUS is one of a family of land-use / transport models described as spatial-economic models. It provides a framework in which to model the interaction between land-use and transport , and can therefore be used to analyse alternative planning and transport policies or combinations of policies. Central to the model is an input-output economic land-use model, which calculates the quantity and location of activities within an area, the likely use and rental price of land and the interaction between different activities in different locations. TRANUS then represents the performance of different modes of transport under these flows. The resulting transport system in turn provides input to the land-use model to influence the operation of the land market and its outcome.

The model has been developed and refined over more than ten years and is now widely used in commercial practice for predicting the impact of land-use and transport policies in cities. Among the most recent are Maracaibo (Venezuela), Bogota (Colombia), and Sacramento (California). Other projects are underway in Lyons and Brussels. Every application involves an extensive process of calibration, that is, testing against historical data on land-use patterns and traffic flows (see below), before any predictions about future developments are attempted.

The present research project is in part an extension of work that was conducted by de la Barra and Rickaby during the 1980's. In one of their earlier research projects (Rickaby, 1987) the authors developed an 'archetypal city region', based on the land-use and road-network characteristics of an array of provincial towns (all of around 75,000 population) in south-east England. Six possible transformations of this archetypal region were proposed, representing the outcomes of different plausible policies for planning control. The patterns covered a spectrum of configurational possibilities from wholesale concentration of population in the single settlement to dispersal into small towns or villages in the hinterland. Between these extremes were arrangements with high-density linear developments along primary or secondary routes. All of these alternatives were modelled and evaluated using TRANUS. In this instance the greatest fuel-saving came where development was concentrated either into the existing urban core or into new or existing villages in the surrounding area.

Scenarios

In the Swindon study we are following a broadly similar approach. One difference from the earlier work is that it is now possible to consider much more radical policies for constraining car-use. The research team is currently working on three possible scenarios for Swindon, each of which combines selected policies for land-use and transport in an attempt to achieve some broad overall goal. In all cases the 'scenario horizon' is set 20 years in the future, i.e. 2016. The base year is 1991 and the modelling will include simulations for four intermediate stages at five-year intervals, and then for the scenario horizon. The population of Thamesdown (effectively Swindon and its hinterland) is projected to grow from 170,000 to 225,000 over the whole period.(an increase of 32%). The workforce is projected to grow from 94,000 to 117,000, while household size is estimated to drop from 2,55 to 2.35 in accordance with the national trend. It is proposed to set higher upper limits on densities in both housing and employment areas than present planning guidelines would envisage.

Scenario A

Scenario A is based on a policy of 'containment and increased density'. This is intended to reflect the kind of 'compact city' proposal that is now widely advocated in the literature.(see above). The scenario aims to achieve this by confining all new development within the Swindon area and prohibiting development in the rural hinterland. Central area development will, in consequence, be at densities higher than at present. These land-use policies are coupled with transport policies that limit car access into central Swindon and by the creation of designated high-capacity busways along radial routes. Provision is also made for park-and-ride facilities around the edge of the town and for the development of cycleways.

Scenario B

In contrast to the 'compact city' approach, scenario B embodies a strategy of 'high density dispersal'. The objective is to investigate the effects of 'exporting' employment and services from the Swindon urban area to hinterland locations which are closer to residential areas, whilst maintaining densities in hinterland centres which are high enough to support the promotion of public transport, cycling and walking in preference to the use of private cars. The plan, with its network of medium-sized settlements, has some affinities with Ebenezer Howard's original idea for a 'federation' of garden cities, but linked by buses rather than railway lines. To achieve this dispersal, development within the town centre will be restricted, and high-capacity busways introduced, both radially and orbitally. Cars will be banned from the town centre and a park-and-ride system put in place. It is possible that new railway stations might be located close to development centres such as Wootton Bassett and Shrivenham to serve local commuters.

Scenario C

The third scenario is in many ways the most controversial and problematic of the three. The aim is to promote widespread dispersal of homes, a policy that might be seen as an acceleration of the existing trend for house-dwellers to migrate to the countryside. Once again there will be severe restriction of development anywhere in Swindon itself. Hinterland development will also be directed, but to a large number of small villages, hamlets, etc., not to the larger satellites. Employment will be dispersed along with residences and a hierarchy of services established to make the various settlements relatively self-contained. The pattern is compatible with increased homeworking or 'telecommuting', though it is not clear how reliably this can be handled in the model.

Park-and-ride schemes will be introduced as in A and B, and the possibility exists for the use of demand-responsive minibus services ('dial-a-bus'), along with HOV's (high occupancy vehicles) along radial routes into the town centre.

Conclusion

It will be clear that TRANUS requires a good deal of empirical data on which to base any future scenarios. These include data on the demographic make-up of the study area, the location and quantity of economic activity, and the operation of the transport system. For the Swindon study the most significant source in addressing the model's needs has been the 1991 U.K. Census. This has been used to obtain a breakdown of the population by socio-economic grouping, by levels of car ownership, and by dwelling-type and tenure. Further information on the quantity of employment and land-use were provided by the local authority. Land-price and commercial rent data were determined from local authority and commercial sources. Transport flow data for each mode along certain key links within the network were derived from the County Council regular monitoring programme.

To model the transport system accurately, TRANUS requires an origin-destination matrix for all modes across the study area. This can be a time-consuming exercise and is one where it is helpful to have a reliable household travel survey. It is also desirable to have detailed data on the use of public transport. In our case, there was a shortage of data in both areas and some time had to be given to complete the picture. Information on public transport is relatively scarce owing to deregulation of the bus service. This is a problem that may recur elsewhere.

We are now at the point (January 1997) where all the data with which to build the first version of the TRANUS model have been collected and converted to appropriate formats. The model is being calibrated against data from the recent past. Since TRANUS comprises a series of interconnected sub-models, with the output from each sub-model providing the input for another, the calibration or testing is an iterative process, which takes some time to complete. Once this has been done, we will begin to test the scenarios described above. The first results are expected in the next few weeks.

References

Breheny, Michael, 1994. 'Defining Sustainable Local Development', Discussion Paper no. 23, Reading: Department of Geography, University of Reading, December.

Breheny, Michael, 1995. "The Compact City and Transport Energy Consumption" in Transactions of the Institute of British Geographers, NS 20, pp. 81-101.

Breheny, Michael and Ian Gordon, 1996. Urban Densities, Planning and Travel Behaviour, paper prepared for the Sustainable Transport Horizons session, annual conference of the RGS-IBG, University of Strathclyde, January.

Commission of the European Communities, 1990. Green Paper on the Urban Environment, EUR 12902, Brussels.

Department of the Environment, 1994. Transport Planning Policy Guidance note 13 (PPG 13). London: HMSO.

Newman, Peter W.G. and Jeffrey R. Kenworthy, 1989. Cities and Automobile Dependence - An International Sourcebook. Aldershot: Gower.

Rickaby, Peter A., 1987. "Six Settlement Patterns Compared" in Environment and Planning B: Planning and Design, 14, pp.193-223.

U.K. Government, 1994. Sustainable Development: the U.K. Strategy, Cm 2426. London: HMSO.

World Commission on Environment and Development, 1987. Our Common Future. Oxford: Oxford University Press.

Urban densities, travel behaviour and the limits to planning

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Summary

This paper reports on a study for the U.K. Engineering and Physical Sciences Research Council, carried out as part of their 'Sustainable Cities' initiative. The study focuses on two related issues: (i) the relationship between densities and travel behaviour, and (ii) local authorities attitudes to, and policies on, densities. Thus, it aims to test both: (i) the veracity of the assumption that higher densities will induce people out of their motor cars and onto public transport, and will result in less travel overall; and (ii) the feasibility of using the planning system to raise densities, whether or not such densities will have the desired effect. Preliminary work on both parts of the study has been reported (Breheny and Gordon, 1996; Breheny and Archer, 1996). This paper summarises progress on these two issues, and points to reasons for being sceptical about both propositions, and hence the likely effectiveness of urban compaction as a strategy for achieving reductions in transport demand.

Introduction

Greater urban compaction is seen by many policy-makers and researchers around the world as a major device for delivering sustainable development. The logic suggests that this will help to achieve two main aims: a reduction in travel and emissions, and a reduction in the loss of open countryside to development. Although the merits of this logic are still disputed, it has gained considerable momentum in both principle and practice. In the U.K., for example, it forms a significant part of the Government's aprroach as outlined in the U.K. Strategy for Sustainable Development (U.K. Government, 1994), and in Planning Policy Guidance Note 13 (PPG13), `Transport', (Department of the Environment, 1994). Government projections (Department of the Environment, 1995), suggesting that 4.4 million additional households will have to be accommodated in England over the next 25 years, have given added impetus to the compaction argument (Breheny and Hall, 1996), as has the target for 60% of new residential development to take place in urban areas (U.K. Government, 1996).

PPG13 has introduced a major change in policy at national level, with an increased emphasis on the interrelationship of land use planning and transport. The thrust of PPG13 is to promote greater urban compaction, and within urban areas to manipulate land uses in order to maximise use of public transport. Central to the whole logic of compaction is the idea of maintaining, and preferably raising, urban residential densities. PPG13 requires local planning authorities to: *'set standards to maintain existing densities and where appropriate increase them'* (para 3.3). However, questions of density have not been central to planning debates for many years. Breheny (1995) has described the use of density controls as a 'lost art'. Planners need to regain that art; they need to understand the prospects for, and consequences of, raising densities. Preliminary findings from the two major issues being addressed in the EPSRC project - densities and travel behaviour and policies on densities - are presented here in turn.

Densities and travel behaviour

A conventional wisdom is rapidly developing amongst both researchers and politicians that higher urban densities will induce significantly less car use, greater patronage of public transport, and hence less fuel use and reduced emissions. The most influential academic studies in the U.K. have been Newman and Kenworthy (1989a and 1989b) and the ECOTEC (1993) study which influenced PPG13. A major motive for our EPSRC study has been the view that this evidence is not sufficiently convincing to use as basis

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for profound policy changes. So far, the study has addressed this question in two ways: (i) through a reworking of Newman and Kenworthy's international data; and (ii) work on U.K. census travel to work data. Only the first is reported here.

In order to test hypotheses about critical influences on differences in per capita energy for cities in different national settings, where real differences in each of the relevant variables can be observed, Newman and Kenworthy (1989a) assembled an impressive data base on a wide range of indicators for 32 cities at the start of the 1980s. Apart from Moscow (the one Soviet city), Singapore and Hong Kong, all of these cities are sited in advanced capitalist economies, but they cover a wide range of income levels, fuel prices, urban forms, transport/planning policies - and levels of energy usage for urban transport.

Despite the wealth of data in this base, Newman and Kenworthy (1989) focus heavily on the ways in which *urban density* (especially when measured at the metropolitan level) seems to affect both the amount of travel and its modal split, and avoid explicit multivariate analysis of possible relations with economic variables. Our re-analysis of their data involved two sets of cross-sectional regressions, with first per capita levels of energy use for urban travel, and then mean urban densities across the metropolitan region as the dependent variables. Just the first of these is reported here. Both the dependent variables and all the key independent variables were expressed in log terms.

Variables	Regression 1	2	3	4	5	6	7	8	9
Constant	6.660 (16.2)	6.192 (23.7)	6.241 (6.9)	5.810 (5.7)	6.148 (6.4)	-1.136 (0.7)	7.748 (6.2)	7.613 (5.3)	7.641 (6.4)
Density (logged)	-1.068 (9.2)	-0.907 (12.1)	-0.376 (5.5)	-0.384 (7.6)	-0.315 (4.5)				
Petrol Price (logged)			-0.753 (6.1)	-0.755 (5.2)	-0.741 (6.4)	-0.657 (2.8)	-1.258 (10.4)	-1.261 (10.1)	-1.066 (9.0)
GDP/head (logged)			0.557 (1.7)			3.502 (6.4)	0.129 (0.3)		
GDP/head: <$7390				0.808 (1.9)	0.550 (1.3)			0.209 (0.4)	-0.071 (0.1)
GDP/head: >$7390				-0.027 (0.0)	0.048 (0.1)			-0.051 (0.1)	-0.164 (0.2)
Rail service (th.veh. kms./head)					-4.475 (2.2)				-8.359 (3.5)
Moscow (dummy)		-2.682 (7.1)	-3.172 (11.2)	-3.042 (9.6)	-3.196 (10.6)		-3.975 (11.2	-3.936 (9.8)	-3.924 (11.7)
Hong Kong/ Singapore			-0.868 (3.4)	-0.738 (2.6)	-1.113 (3.5)		-1.674 (5.5)	-1.636 (4.6)	-2.036 (6.4)
N	32	32	32	32	32	32	32	32	32
Adjusted R^2	0.731	0.898	0.977	0.977	0.980	0.743	0.952	0.958	0.965
Stand. error	0.58	0.36	0.17	0.17	0.16	0.57	0.24	0.25	0.21

Table 1: Regressions of private petrol use on density, income and fuel prices

Notes: 1. Dependent variable is private use of motor spirit expressed in millions of Joules per person, and logged; 2.Bracketed values are t statistics; 3. All data are taken from Newman and Kenworthy (1989) and relate to 1980.

The set of regressions reported in Table 1 take as their dependent variable the one measure of energy use available for all 32 cities, namely petrol consumption in private vehicles. The regressions start with a version of the simple bivariate relationship with mean population density for the metropolitan region, confirming that this is indeed highly significant. Including a dummy variable for the unique case of Moscow (in regression 2 of Table 1) greatly improves the fit of the model, without substantially altering the estimated relationship between fuel usage and density.

Substantial residual variance still remains, but most of this is absorbed when price and income variables are added to the equation (in regression 3). Hong Kong and Singapore now also emerge as deviant cases, for which a second (joint) variable is added to the model; once this is done the (positive) relationship with income becomes rather weak, and only evident at all among the cities with below average incomes. As hypothesised, however, a strong (negative) relationship is evident between energy use and fuel prices, with an elasticity of about -0.75. In terms of statistical significance its influence appears comparable to that of density. Moreover, inclusion of this variable serves to greatly reduce the estimated elasticity of energy use with respect to urban density, to around -0.35.

The possibility that transport policies could also exert an effect on energy use, independent of urban form, was investigated. Only the annual vehicle mileage per head of buses/trams and trains proved at all significant and worthy of retention in the equations reported here. Predictably its influence is strong in the private petrol use equation (from regression 5 in Table 1). In the light of evidence that density is a endogenous factor, regressions 6-9 in Table 1 exclude this variable, yielding almost equally good fits. Higher coefficients on the price variable then point to a long-run price elasticity of around -1.

These results suggest that both densities and fuel prices can exert substantial effects on levels of fuel usage in transportation, with the possibility that policy interventions affecting either variable may increase the energy efficiency of cities. However, this re-analysis of Newman and Kenworthy's data suggests that they have been rather one-eyed in their focus on urban density as the key influence on energy use in urban transport, and that they have significantly over-stated both its impact and its independence from situational and economic factors. Controlling for the effects of income and transport cost variation does still leave an important relationship between urban density and energy consumption. But, very large increases in density now seem to be required to substantially reduce energy use, and since no direct measures of planning activity were included in the analyses, we cannot conclude that these densities can be manipulated in order to achieve that effect - in the way that fuel prices clearly can be manipulated by varying rates of petrol tax. The pressures of private demand lead in the opposite direction, and in the UK, at least, past research does not demonstrate a capacity for the planning system to effectively resist these.

Densities in local planning policy

Given that local authorities are now under considerable pressure to promote higher densities, it is important that we know what policies they have in place and how they are responding to the new policy regime. This knowledge may cast some light on the feasibility of the Government's approach - for example, do local authorities welcome the idea of higher densities, or is there resistance to raising densities? If there is resistance, why? It might also identify 'best practice' measures of density or standards that might help local authorities to adopt more effective density policies.

The assumption here is that by now there should be some evidence of a local authority response to the Government's desire for higher densities. The compaction question, including densities, has been an issue amongst planning academics and practitioners since about 1989. The draft version of PPG13, urging higher densities, was issued in 1993. The final version was issued in March 1994. It is reasonable to expect some evidence of the new agenda in adopted density standards, particularly in informal standards, and in changed attitudes following PPG13. A survey was used to gather this evidence. A questionnaire was sent out to all 385 English District Councils and London Boroughs (Isles of Scilly and City of London excluded) during May 1996. The response rate was 285 or 78.1%.

The term 'measure' will be used here to refer to the range of ways in which densities may be recorded. Thus, a density measure might be, for example, persons per acre, or dwellings per hectare, or habitable rooms per acre. A density 'standard' refers to a prescribed density level that planners attempt to achieve. Standards can be expressed numerically, often as a range. Some authorities have standards expressed non-numerically, such as 'a level consistent with surrounding residential development'. Both numerical and non-numerical standards may be stated formally in local plans, or used as notional standards as criteria in judging planning proposals. A density 'level' refers to actual achieved density values. Respondents were asked if they have: (a) formal numerical standards in the local plan; (b) current numerical 'notional' standards, including recent changes; (c) non-numerical standards; and (d) estimates of achieved density levels 'over the last ten or twenty years'.

Overall, Breheny's (1995) view about the 'lost art' of densities does seem to be supported by the evidence, because just 93 (32.6%) of authorities have plan-based numerical density standards. This figure is boosted by London authorities, where all but three have numerical standards. A total of 186 (65.0%) authorities have current notional standards, while 105 (36.8%) provided details of previous notional standards. Altogether, 228 (80.0%) authorities have or have had some form of numerical standard. Some 151 (53%) authorities have non-numerical standards, while 82 (28.8%) authorities have neither.

The specific density measures used by authorities are of three types: (i) **dwellings per hectare** (dw/ha). This measure is used by the large majority of authorities. The measure is popular despite the fact that, in principle, it is inflexible; (ii) **habitable rooms per hectare** (hrh). This is used by a total of 27 authorities, with 25 using in as a plan-based measure, 9 as a notional measure and 7 as a previously used notional measure. Use of this measure is very much a London phenomenon. The standard is flexible and applicable over a range of situations; (iii) **bedspaces per hectare** (bsh). This is a rather rare measure, being used by just two authorities.

The average **plan-based standard** for authorities with dw/ha measures was 28.8. For authorities using hrh measures, the average density is 191.8hrh. The overall averages for **current and previous notional standards** are 27.6dw/ha and 26.8dw/ha respectively. On the hrh measure, the average current notional density is 201.6hrh, compared to a previous notional density average of 210.4hrh. The average **achieved density** for the 161 authorities providing a response is 29.0dw/ha. For the hrh version of achieved density levels, the average is 234.6hrh.

Table 2 illustrates an attempt to identify any geographical pattern in achieved densities. It ranks counties (full ranking is given in Breheny and Archer, 1996) according to the average achieved density of the respondent districts within each county, measured in dwellings per hectare (thus, excluding Greater London). Also given is the range of density standards used within each county.

County	Average achieved	Achieved range	Categories
1. Bedfordshire	36.0	30-40	} 'Pressured'
2. Kent	36.0	25-63	}
.	.	.	
21. Tyne and Wear	29.0	27-31	} 'Urban Industrial'
22. West Yorkshire	29.0	25-37	}
.	.	.	
41. Northumberland	22.0	16-30	} 'Non-Pressured'
42. Lincolnshire	18.0	12-25	}
England	29.0	12-63	

Table 2: Sample of tanked achieved densities - average and range of districts in each county (dw/ha) **Note:** County average is the average for districts in that county; range is range of district averages; London excluded because values not available in dw/ha. East Sussex excluded because no district gave figures for achieved densities

Clearly, there is a considerable variation in average achieved densities across England. The county averages dampen down the district extremes to some extent. Nevertheless, the county values do show quite remarkable differences; from Bedfordshire, with 36 dw/ha, to Lincolnshire, with just 18 dw/ha. The top group of counties are mainly in the pressured South East or the still more pressured counties immediately beyond the South East boundary. The second group, with average densities varying from, say, 30dw/ha down to 27 dw/ha, contains a number of metropolitan, industrial areas, where higher urban densities will have prevailed over a long time, but where land has been relatively plentiful. A high proportion of development in these areas is on re-used urban sites. The third group contains all the remaining counties, with relatively low achieved densities in non-pressured shire counties, where there has been much less political pressure to preserve greenfield sites.

Those authorities who have non-numerical density standards were asked to give details of the criteria that they use. The dominant criteria relate to questions of local amenity - the density of new development has to be consistent with the surrounding area. This implies that standards are often used as a defensive mechanism, to maintain the quality of existing urban fabric. In the face of Government pressure to raise densities, local authorities are often resisting further intensification, and are using density standards to do so.

Another way of measuring local authority response to PPG13 and the broader urban compaction debate is to assess the degree to which recent density standards have changed. Have these increased, as might be expected given the pressure to promote urban compaction policies? Or has this pressure been resisted and density standards maintained at traditional levels? Average values have been used to check whether standards and levels have changed over time. The following assumptions have been made: (i) comparison of plan-based standards in plans adopted pre- and post-1993 ought to reflect any responses to the compaction debate; (ii) comparison of previous and current average notional standards ought also to reflect any recent changes to standards; and (iii) comparison of average current notional and achieved standards ought also to reflect changes.

Table 3 shows the results. In the first case, plan-based standards appear to be static, while the third case suggests that current notional standards are lower than density standards achieved in the past. Only the second comparison suggests a small rise in the average notional standard being used. There is little evidence here, then, to suggest that the environmental imperative is having much effect in raising density standards. Breheny and Archer (1996) give a detailed version of this analysis, referring to specific cases.

	Earlier Average	Later Average	%Change
(i) Pre and Post 1993 Plan-Based	30.0dw/ha	30.0dw/ha	0.0%
(ii) Previous and Current Notional	26.8dw/ha	27.6dw/ha	+3.0%
(iii) Achieved and Current Notional	29.0dw/ha	27.6dw/ha	-4.8%

Table 3: Three comparisons of changes in densities - averages for all districts

Respondents were asked about their responses to PPG13. Some 76 authorities, or 26.6%, replied that they had reviewed their policies in response to the guidance, while 190 authorities, or 66.7%, had not (19 did not answer the question). Only 13 of 285 authorities have actually increased numerical standards in response to PPG13. Just 29 authorities intend to consider PPG13 as part of their local plan review. Some 183 authorities suggested they envisage problems in raising densities. The major reasons revolve around potential loss of amenity or loss of quality in existing residential areas, or fears over town cramming.

For advocates of urban compaction, evidence from this survey must make depressing reading. Clearly, many authorities do not use density standards at all, and where they are used it seems to be in a rather half-hearted, pragmatic fashion. Where quantitative evidence on standards exists, it shows no discernible trend to higher standards. The qualitative evidence shows a remarkable lack of interest in PPG 13 and a tendency for density policies to be used to protect the status quo rather than to promote change.

Conclusion

The overall effect of the preliminary results presented here is to cast doubt on the urban compaction case that dominates planning policy. The evidence on travel behaviour suggests that increasing urban densities might have some effect on reducing overall travel, but that manipulation of fuel prices would have a greater and infinitely quicker effect. This confirms the suspicion that planners are expected to deliver a solution in the absence of the political will to grasp the more obvious, but politically unacceptable, answer. The review of density policies has suggested that these will be difficult to implement, even if they are seen as technically appropriate. Local authorities see density standards as protective devices, not as tools to effect radical policies. This is a classic example of the 'implementation gap' that so often undermines policy (Breheny and Gordon, 1996).

References

Breheny, M. (1995) Urban Densities and Sustainable Development, paper presented at the conference of the Institute of British Geographers, Newcastle-upon-Tyne.

Breheny, M. and Archer, S. (1996) Urban Densities, Local Policies and Sustainable Development, paper presented to the 36th Congress of the Regional Science Association International, Zurich, August.

Breheny, M. and Gordon, I. (1996) Urban Densities, Planning and Travel Behaviour, paper presented to the annual conference of the Institute of British Geographers, Glasgow.

Breheny, M. and Hall, P. (eds) (1996) The People - Where Will They Go? National Report of the TCPA Regional Inquiry into Housing Need and Provision in England, London: TCPA.

Department of the Environment (1994) Planning Policy Guidance 13: Transport, HMSO, London.

Department of the Environment (1995) Projections of Households in England to 2016, London: HMSO.

ECOTEC (1993) Reducing Transport Emissions Through Planning, HMSO: London.

Newman, P. and J. Kenworthy (1989a) Cities and Automobile Dependence: a sourcebook, Aldershot: Gower.

Newman, P., and Kenworthy, J. (1989b), Gasoline Consumption and Cities - A Comparison of U.S. Cities with a Global Survey, Journal of the American Planning Association, 55, 1, 24-37.

U.K. Government (1994) U.K. Strategy for Sustainable Development, London: HMSO.

U.K. Government (1996) Household Growth: Where Shall We Live?, Cm 3471, London: The Stationery Office Ltd.

Guidelines for the design and operation of natural and mixed-mode ventilation systems in commercial buildings

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Summary

There is growing evidence that many cities around the world are becoming increasingly concerned about urban air quality and pollution. At the same time there is concern over the health, comfort, energy costs and environmental impact associated with air conditioned buildings. Such developments mean that future commercial buildings in the UK and elsewhere are more likely to have a naturally ventilated or mixed mode ventilation environment rather than full air-conditioning. However, there are a number of uncertainties in the design and operation of such systems which could lead to high risk solutions and, or, high design costs. This paper will describe a project, the aims of which are to provide valuable information and guidance to this debate, including the following :-

- Assess health and comfort : to investigate the health and comfort of workers in commercial buildings which have full or part natural ventilation and to relate human response to the physical environment (thermal conditions, ventilation rates, air quality, noise and daylight), the building design (space planning, building form and thermal mass) and the organisation (job type, management structure).
- Inform design : to provide evidence to inform designers on limitations for natural ventilation and selection of mixed mode alternatives.
- Assess design practices : to assess the design skills, design procedures and design tools that are needed to produce naturally ventilated and mixed mode solutions and to compare these with current design practice.
- Assess the costs and benefits : to compare the costs and benefits of natural ventilation and mixed mode solutions in relation to full air-conditioning solutions.

The project seeks to fulfil these aims by conducting detailed case studies in eight buildings, four designed to meet 1990 Building Regulations requirements, and four designed around innovative natural or mixed mode ventilation requirements.

Origins of the project

The project originated in what might be termed 'need' and 'method'. To improve the sustainability of built environment the building team needs a clear idea of what measures least impact on the environment, meet users' requirements, and how they can be implemented. Case studies of existing building can go a considerable way to meeting this need. However, to be valid and useful they require a well founded method that results in clear understandable lessons. Various participants in the current work, having been party to the development of appropriate methods in earlier projects (Energy Performance Assessment (EPA)[1] field studies of passive solar buildings for the DTI ETSU, and the case studies of air conditioned office buildings for the SERC/DTI LINK programme[2]), were well placed to design and execute field studies of naturally ventilated and mixed-mode office buildings as a contribution to the EPSRC's sustainable cities initiative.

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Aims

In terms of the individual buildings studied and how natural and mixed mode ventilation is applied in office buildings the project's aims are to :-

- Assess health and comfort : to investigate the health and comfort of workers in commercial buildings which have full or part natural ventilation and to relate human response to the physical environment (thermal conditions, ventilation rates, air quality, noise and daylight), the building design (space planning, building form and thermal mass) and the organisation (job type, management structure).
- Inform design: to provide evidence to inform designers on limitations for natural ventilation and selection of mixed mode alternatives.
- Assess design practices : to assess the design skills, design procedures and design tools that are needed to produce naturally ventilated and mixed mode solutions and to compare these with current design practice.
- Assess the costs and benefits : to compare the costs and benefits of natural ventilation and mixed mode solutions in relation to full air-conditioning solutions.

Research design

To fulfil these aims the study has adopted a method previously developed as part of the SERC/DTI LINK investigation (EPSRC, GR/H38645 1995)[2] of occupant health and comfort in eight inter-linked case studies of air-conditioned office buildings. However, a number of important adjustments and additions have been made to the earlier procedures. The method comprises a series of modules which work in conjunction with one another to provide a multidimensional evaluation of a building and an extensive database for between buildings analysis. The modules are :-

- Building Selection : prior to the monitoring phase of the study a literature search is conducted which, along with personal approaches to known building owners, allows the investigators to identify potential candidate buildings for the case studies against an established list of selection criteria.
- Preliminaries and Design Study : having met the study's broad selection criteria each candidate building is inspected in some detail to ensure that its design and operation, particularly those aspects relating to ventilation, are free from major problems. A 'monitoring plan', outlining the building's environmental strategy and detailing how the study's 'Guide to Procedures' will be implemented, is prepared and agreed with the building owner/occupier. One or more members of the design team are interviewed and a 'design statement' prepared, detailing the building's origins, precedents, and pertinent aspects of the design process.
- Occupant Study : satisfaction and health at work reflect the interaction between the individual, the built environment, and the organisational setting within which work is performed. This component is concerned with measuring, recording and assessing environment quality from the individual's point of view, and with studying the interaction between the individual and the environment. The work is closely linked to the long and short term physical monitoring.
- Long Term Physical Monitoring : various aspects of the physical environment, throughout the building under investigation, are monitored for an extended period of up to 12 weeks. These measures are then related to the subjective evaluations made during the occupant study, as well as informing the design of the short term monitoring studies.
- Short Term Physical Monitoring : whilst long term measures of indicative variables at multiple locations may provide some idea of comfort conditions throughout a building, such measures are not sufficient to give an insight into how a ventilation strategy works, or the reasons why discomfort or certain control behaviours occur. To meet these requirements, situation specific short term experiments are designed and conducted in localised areas within the case study building.
- Cost-benefit Analysis : it is generally thought that natural ventilation can provide a healthier environment at lower capital and running costs in comparison to air-conditioning. This component seeks to

quantify the various benefits and costs in order to form an objective evaluation of natural ventilation in occupied buildings. Although similar exercises have been carried out in other building evaluation projects performed by the members of the research team[1] this module did not appear in the LINK study upon which the current methodology is primarily based.

- Analysis : the data derived from each building case study will be analysed at two junctures in the project. The first, the building specific analysis, will be completed at the end of the particular case study. This will allow an interim report to be given to the building owner, or occupier, regarding the performance of their building. The second, the between buildings analysis, will be performed once monitoring in all eight buildings has been completed and the full range of occupant and physical environment data become available. Apart from informing the cost-benefit analysis such analysis will allow a fuller investigation of the relationship between comfort and the physical environment.
- Reporting : a series of distinct reports will be prepared as part of the project. Firstly, a building specific report will be prepared at the end of each case study which describes the environment within the building and evaluates the performance of the ventilation strategy. The eight individual building reports will then be collated to form one section within the second level of report, the between buildings report. This report will seek to convey the findings from the study as a whole and to establish lessons about natural ventilation which may be of use to the wider group of building designers, clients, and those responsible for building related regulations. Ultimately these will be communicated to various audiences by means of short 'best practice' type reports, academic papers and journal articles, as was the case in the earlier EPA and LINK studies.

Timescale

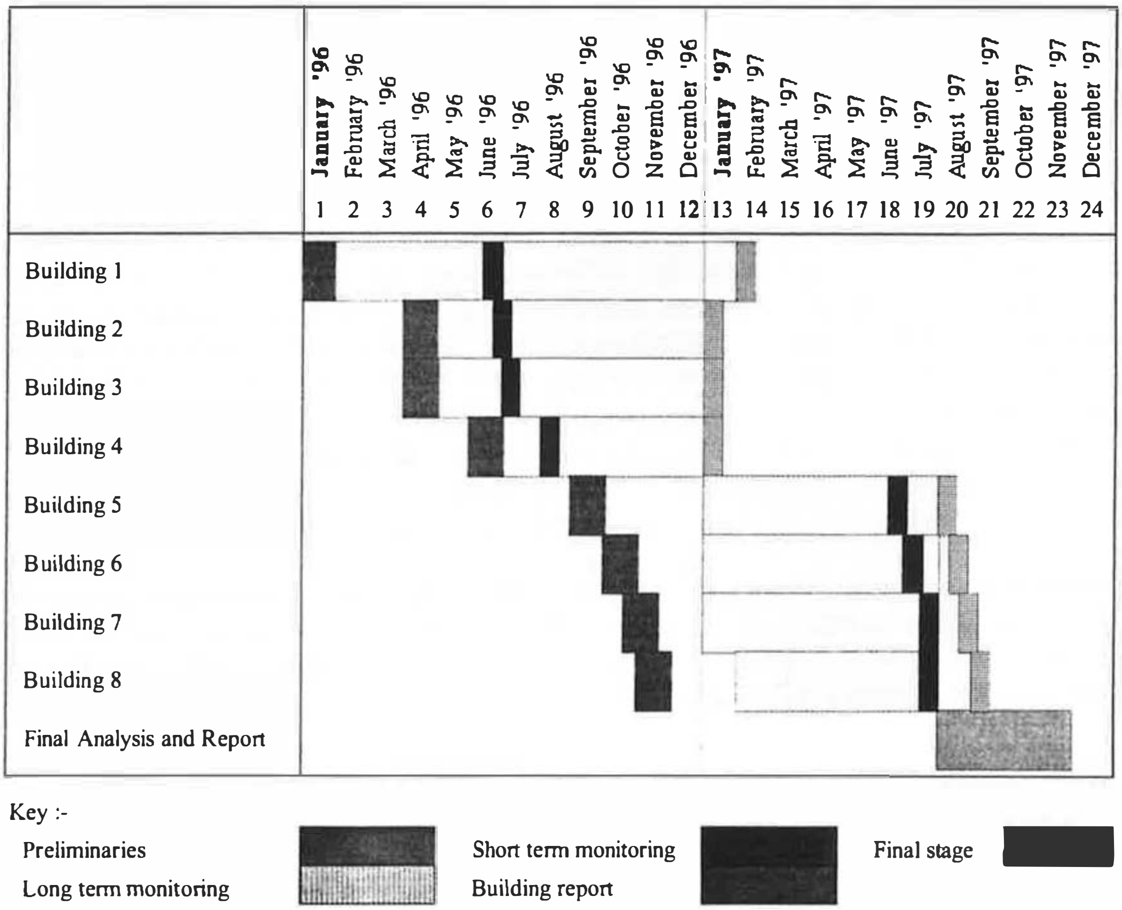
A brief schedule for the project is presented below. At the time of going to press (January 1997) monitoring in the first four case studies is complete and the associated individual building reports are in preparation. The interim between buildings analysis is in hand, as is the comparative analysis with the earlier LINK case studies.

Issues of interest

As mentioned above, the study's methods are closely based upon the preceding study in air conditioned offices. A number of alterations and additions have been made and some of these are now discussed.

The physical monitoring

The LINK study had two distinct levels of monitoring, long term (up to twelve weeks) building wide monitoring of air temperature, and short term (two weeks) detailed monitoring of the thermal environment, air quality and related factors. Whilst the current study incorporates both levels of monitoring it differs in some respects in its short term studies. In the earlier study, the short term monitoring was principally configured to evaluate the physical environment of contrasting clusters of 'healthy' and 'unhealthy' occupants identified by means of a Geographical Information System (GIS) analysis of questionnaire replies. Whilst a similar procedure is used in the natural ventilation studies, the short term measurements have the additional role of evaluating the operation and performance of specific elements in the ventilation strategy. For instance, where the ventilation strategy calls for the sequential operation of windows, ventilators or shutters and predicts that air will move in a particular fashion through the building then a tailored experiment is conducted to evaluate this. Where possible the short term experiments are designed with regard to the findings from GIS analysis and interviews of selected occupants, and are analysed in conjunction with computer simulations (thermal and airflow). Such tailored experimentation formed an essential part of the EPA studies and enabled a number of important lessons to be identified[6].



Project schedule

Pollutants

Although some of the pollutants of interest were assessed in the LINK study it was felt that more could be done in the present study to relate internal and external measures and to evaluate them in terms of external weather.

Several pollutants are considered at present to be a health risk. Current concern centres on particulate matter which consists of particles below 10 microns in diameter (PM10). It is suspected that those particles of 2.5 microns diameter and below may also cause health problems. Nitrogen oxides are aggressors to asthmatics as are ozone and sulphur dioxides. Benzene and Volatile Organic Carbon compounds (VOC) may cause cancer and are also a cause for concern. Dust mites may also cause allergies. External pollutants will generally only be at risk levels during a pollution episode, unless the building is in an unusual situation, e.g. in the plume of a power station. Internal pollutants may be generated at high concentrations decaying over time e.g. carpet glue solvents, or, as is the case of photocopiers, in one place at irregular times.

The current pollution monitoring seeks to show whether pollutants are present in a building at sufficient levels to cause concern.

Air conditioned buildings generally have air intakes situated on the roof, so their main air supply is expected to contain only background levels of pollutants, naturally ventilated buildings by their nature take in air from all levels around the building envelope and may draw traffic based pollutants into the building from near the road or car park and then distribute them throughout the building. The pollution monitoring also seeks to investigate whether this is the case or not.

The occupant study

One of the findings of the LINK study, which was commensurate with earlier literature, is that only a proportion of symptom reporting is related to the built environment. Pursuing this further, the current study has sought to better identify the 'building component' by adding a number of non-environmental measures specific to the individual occupant, which the literature directly states may be related to symptoms, or which the research team has inferred as being potentially related to symptoms. These include details about the person's intrinsic motivation, physical fitness regime, life events over the preceding two years, allergies, use of nasal sprays, and use of oral contraceptives. Further measures have also been included concerning occupants' use of windows and other ventilation devices.

Use of space

The LINK study included an evaluation of space use, with particular emphasis on the relationship between health reporting and spatial integration/segregation, and health and workspace area and volume. With the shift in emphasis in the current project towards understanding the operation of ventilation measures, the spatial investigations have been sacrificed to provide resources for more extensive pollution monitoring and short term experimentation. Workspace area and volume will be derived for each occupant by means of the GIS representation of each building.

Design study

In the earlier EPAs, interviewing members of the design team and preparing a 'design statement' on the case study building's origins, design process, and environmental strategies was found to be helpful, both for modifying the research design prior to monitoring and for interpreting the eventual results. Despite the coverage the EPAs received[3,4,5] it is debatable whether their design lessons have had much impression on practice. If the wheel is not to be continually reinvented and mistakes repeated it is important to understand how designers conceive their environmental strategies and how they evaluate their likely performance prior to implementation. Apart from its other work, the design study seeks to identify what precedents were used in developing environmental measures, whether or not designers were aware of relevant contemporary research, and what the obstacles were to the use of research findings.

Cost benefit study

Clearly there are environmental and possibly health benefits with buildings which avoid air conditioning, or where background mechanical ventilation is used in a mixed mode manner without mechanical cooling. Since in many cases the construction costs of naturally ventilated and mixed mode buildings are greater than for simple air conditioned equivalents, it is important to quantify the overall cost benefits or disbenefits (in terms of both capital and running costs) of the naturally ventilated/mixed mode option. This project is therefore developing a method to enable a cost benefit analysis to be made, which compares directly the capital and running costs of each of the naturally ventilated/mixed mode case studies with a notional air conditioned equivalent.

Since an air conditioned building would be designed quite differently to one which is naturally ventilated (a compact plan as against a narrow plan, for example) the definition of the air conditioned equivalent is not straightforward. In this project, the air conditioned equivalent will be defined as a building with the same floor area, number of floors, percentage glazing and U-values as the case study, but with as compact a plan as possible (i.e. a square floor plate) having a simple air conditioning system, such as a fan coil unit system, in place of a conventional wet radiator heating system.

Quantity surveying norms will be used to estimate the capital and maintenance costs of each of the actual case study buildings and their air conditioned equivalent on a per square metre floor area basis, and the thermal simulation program HTB2 will be used to estimate the typical annual cost for fuel for both. These results will then be compared with each other and with any data available on actual capital and running costs of the case study buildings. In this way the cost benefits and disbenefits of the natural ventilation/mixed mode option over the air conditioned option will be clearly highlighted. Whilst it is appreciated that full life cycle costing of each option could produce a more rigorous analysis, the project does not have the resources to carry out this work, especially as it should include sensitivity analyses of the effects of the assumptions made.

References

1. P E O'Sullivan, A Hildon, D K Alexander, J Palmer, and N D Vaughan - *Energy Performance Assessements. A Guide To Procedures : Volume 2 - Non-domestic Buildings*, Harwell : ETSU. Report No. ETSU S 1160-P2 (1992) pp102 + extensive appendices.
2. P.J.Jones, N.D.Vaughan, T.Grajewski, H.G.Jenkins, P.E.O'Sullivan, W.Hillier, A.Young and A.Patel.*New Guidelines For the Design of Healthy Office Environments*. Summary Report to the SERC/DTI, Reference : GR/H38645, March 1995.
3. Vaughan N D and Jones P - *Making the most of passive solar design.* Building Services, Vol.16 No.11, pp39-41, November, 1994. ISSN 0951-9270.
4. The Department of Trade and Industry. The Energy Performance Assessments : a series of 31 Solar Building Studies and supporting Technical Reports. ETSU, Harwell (1990-93).
5. General Information Leaflet 16 : Using Solar Energy in Schools. BRECSU Best Practice Programme. Garston : BRE 1993. pp2.
6. D K Alexander, N D Vaughan, P Jones, H Jenkins and P E O'Sullivan - *Technical Report : Looe Junior and Infants School, Report number ETSU 1163/1*, ETSU, Harwell (1990) pp90.

Acknowledgements

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The prediction of sound levels and room acoustic parameters using a ray-tracing model

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Abstract

This paper presents a brief summary of research into the use of computer models for sound field prediction in enclosed spaces. A ray-tracing model, REDIR RT, previously used to predict sound propagation in enclosed spaces, has been enhanced to simultaneously predict temporal and spatial room acoustic parameters. The predictions of REDIR RT were compared to those of the classical method of Eyring in a hypothetical reverberation chamber to demonstrate the validity of the model.

The reverberation time in a recording studio was predicted by REDIR RT across six octave bands using various levels of representational detail. It was found that averaging the absorption of each room surface gave a similar prediction accuracy to that obtained by modelling the individual areas of absorption.

Predictions in a concert hall were undertaken across six octave bands using a simplified representation, as justified by the recording studio results. REDIR RT predicted the reverberation time, averaged across the octave bands to an accuracy of 13%, and for the 1 kHz octave band an accuracy of 11% was obtained. These results were significantly more accurate than those obtained using the Eyring formula Early decay time, and sound propagation were also predicted to a high degree of accuracy. These results demonstrated that both the spatial and temporal characteristics of the sound field can be accurately predicted simultaneously using one consistent set of data on geometry and absorption.

Introduction

The acoustic design of a space is important both for the purposes of compliance with the Noise at Work Regulations and to optimise comfort of occupants in the case of work spaces; and to maximise the enjoyment of listeners and performers in performance spaces. To fully describe the sound field in an enclosed space both spatial and temporal acoustic characteristics are required. The spatial characteristics are best described using sound level distribution and reverberation time is a typical temporal characteristic. Ideally a computer model should be capable of simultaneously predicting sound levels and temporal acoustic parameters. However, previously, it has been found difficult to accurately predict the complete sound field in an enclosed space using a consistent room description (1).

Many computer models have been developed to predict sound propagation in work spaces (2,3,4), but little has been published concerning the prediction of reverberation time. The computer model RAYCUB-DIR REDIR (5) was designed to predict sound propagation in workspaces and was extended for this investigation to model reverberation time, creating REDIR RT. This paper presents a validation of REDIR RT in two enclosed spaces across the octave bands for the following room acoustic parameters: reverberation time (RT); early decay time (EDT); and sound propagation (SP).

The REDIR RT model

REDIR RT is an ray-tracing model which has extended the representational ability of the Ondet and Barbry model (4) to include sound source directivity and barrier diffraction (5). REDIR RT was further developed to predict the sound field more completely by simultaneously predicting SP, RT, EDT and the Clarity Index using a single set of data for each octave band. To achieve this the entire energy

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decay curve was predicted by geometric acoustics using a 90% energy discontinuity (6). An energy discontinuity occurs when the amount of energy remaining is assumed to be insignificant. This will occur after the sound has been reflected a related number of times, the reflection order n, as calculated from the energy discontinuity percentage as shown

$$n = \frac{\ln\left(1 - \frac{p}{100}\right)}{\ln(1 - \alpha_{av}) - hl}$$

where p is the energy discontinuity percentage, α_{av} is the average acoustic absorption coefficient of the surfaces and fittings, h is the air attenuation coefficient (dB/m) and l is the mean free path length for the room.

REDIR RT was validated by comparison with classical acoustic theory in a simple hypothetical space. This showed the model to be accurate in a simple space. The model was then used to predict the sound field in two performance spaces, a recording studio and a concert hall. The predicted values were compared with measured values.

The hypothetical space predictions

If a model is to be developed for any type of enclosed space it should first be tested in the simplest possible space, hence REDIR RT was used to predict the RT in a hypothetical reverberation chamber, for comparison with the predictions of the classical Eyring formula. The chamber was assumed to be 7 m long, 6 m wide and 5 m high with evenly distributed absorption. The model was tested for three different values of the absorption coefficient: α=0.05, α=0.10 and α =0.20. The sound source was treated as omni-directional and was positioned in one corner of the space. The receiver point was taken to be in the corner of the space furthest from the source.

Table 1: Comparison of REDIR RT and Eyring RT Predictions in a Hypothetical Reverberation Chamber with Increasing Absorption.

	α=0.05	α=0.10	α=0.20
REDIR RT	2.92 sec	1.52 sec	0.79 sec
Eyring	3.08 sec	1.50 sec	0.71 sec

Table 1 shows that for an average absorption coefficient of 0.05, as in a typical reverberation chamber, the difference between the two predictions was only 0.16 seconds or 5.5%. For α=0.1 the difference was 0.02 seconds, for α=0.2 the difference was 0.08 seconds. This demonstrated that REDIR RT was accurate in the simplest possible space, showing the same high degree of prediction accuracy as recorded by Hodgson (7), and suggests that the model could be of practical use in more realistic spaces.

The performance space predictions

A recording studio and a concert hall were used for the measurements and predictions in the octave bands 125 Hz to 4 kHz. For all of the predictions absorption coefficients taken from standard texts were used. In the recording studio, RT was measured and predicted; in the concert hall RT, EDT and SP were measured and predicted.

The recording studio

The recording studio was still under construction when the measurements were taken. The shell was completed, but the room was empty except for the acoustic treatment of the walls with framed mineral wool. The studio was 4.88 m long, 4.15 m wide and 2.4 m high. The floor was a screed concrete construction, with a plasterboard ceiling suspended in a metal frame with a 0.27 m air gap behind. The brick walls were covered with painted plaster and on the full width of each surface was a mineral wool frame at a height of 0.71 m to 2.14 m, see Figure 1. In one wall was a triple glazed window 2.0 m by 1.2 m. A loudspeaker was positioned in one corner of the room, facing the corner, while measurements were taken at six positions at a height of 1.6 m, see Figure 1.

The reverberation time predictions

The RT measurements and predictions were averaged over the six receiver positions at all frequencies. Figure 2 shows the measured and predicted values, together with the values predicted by the Eyring formula. The variation with frequency of the Eyring predictions was consistent with that measured, but the times were approximately 0.3 seconds longer than the measured RTs, giving an overall error of 87%. The REDIR RT predictions were within 0.1 seconds of the measured RT at all frequencies, giving an overall error of 13%.

The over-prediction of the Eyring formula can be explained by the framed mineral wool creating an uneven distribution of absorption that could not be represented by the Eyring formula which is based on the average room absorption coefficient.

REDIR RT was rerun using the average absorption coefficient for each room surface rather than individual coefficients for each area of absorption. The results were similar to those produced using the original absorptive patch representation. The model was also run using the average room absorption coefficient; in this case the predicted RTs were significantly different from the measured values and the average error across the octave bands was 22%. These results demonstrate that there is a point at which greater representational detail gives no corresponding improvement in the predictions for an averaged room acoustic parameter such as RT.

The concert hall

The empty concert hall was 34.9 m long, 17.7 m wide and 11.8 m high, the roof was barrel vaulted and the minimum wall height was 7.3 m. The walls were constructed of plastered and painted brickwork, the floor of wooden boards and the ceiling of plasterboard. Located along the two longest walls were five evenly-spaced windows with undrawn curtains. At one end of the room there was a full width wooden stage 1 m high with a full height heavy velvet curtain across the back stage wall. On the opposite wall was a partial height curtain, see Figure 3. The sound source was omni-directional and was positioned 23 m from the end wall and 8.39 m from the side wall, at a height of 1.7 m, see Figure 3. The loudspeaker was connected to a computer measurement system (MLSSA) which was used to measure SP and other acoustic parameters at receiver positions along the hall, at a height of 1.25 m.

The REDIR RT model represented the room as a parallelepiped shaped space of volume equal to that of the actual space with absorptive patches corresponding to the curtains at each end of the room. The windows and their curtains contributed to an average absorption coefficient for each of the long side walls.

The predictions

For reasons of brevity predictions at each receiver point along the space are presented for the 1 kHz octave band only. Figure 4 shows the measured and predicted RT and EDT values at 1 kHz at points along the hall. The predicted RT averaged over all receiver positions was 2.70 seconds compared with 2.58 seconds for the measured RT, an error of 4.7%. The Eyring formula predicted an RT of 3.92 seconds, an error of 51.9%. The measured EDT rises rapidly close to the source, increases more slowly as the source-receiver distance increases, and eventually decreases, giving results similar to those found by Kang (8) in corridors. The REDIR RT predictions of EDT increased up to a point 12 m from the source, then remained constant at greater source-receiver distances.

Figure 5 shows the measured and predicted SP curve for the 1 kHz octave band. The sound pressure levels were predicted by REDIR RT to within 2 dB of the measured levels at all receiver positions. These results demonstrated that the REDIR RT model can be considered accurate for sound level prediction, as measurements are known to vary by up to 2 dB due to measurement error (9).

Summary

REDIR RT, a model developed specifically for the prediction of sound levels in factories has been extended to simultaneously predict spatial and temporal room acoustic parameters including sound propagation, reverberation time and early decay time in enclosed spaces. In this study performance spaces were considered with particular emphasis on reverberation time and sound propagation.

In the recording studio reverberation times only were predicted. The results suggested that the Eyring formula could not accurately model a room with unevenly distributed absorption, the RT being consistently over-predicted with an overall error of 87%. The REDIR RT predictions were reasonably accurate with an error of only 13%. When a less detailed representation of the room was used very similar predictions resulted. Hence, a simple representation was used in the concert hall predictions.

For the concert hall REDIR RT used a simple representation of the space to simultaneously predict the various room acoustic parameters investigated. The reverberation time was predicted with an average error of less than 13%, compared with an error of 29% using the Eyring formula. For the 1 kHz octave band REDIR RT predicted the RT to within 6% of the measured value. Sound propagation was also accurately predicted, with an average error of less than 2 dB for all octave bands. These results demonstrated the spatial prediction accuracy of REDIR RT.

Overall it would appear that the Eyring formula could not accurately predict the RT in rooms when one or more wall areas were significantly more absorptive than the other surfaces. The REDIR RT model was found to accurately predict simultaneously the spatial and temporal room acoustic parameters in such spaces, using a single representation of the space.

References

1. M. HODGSON, Journal of the Acoustical Society of America, 97 (1), pp.349-353, 1995
2. E. LINDQVIST, Acustica 50, pp.313-328, 1982
3. U. KURZE, Journal of Sound and Vibration, 98(3), pp.349-364, 1985
4. A. M. ONDET and J. L. BARBRY, 85(2), pp.787-796, 1989
5. S. M. DANCE, J. R. ROBERTS and B. M. SHIELD, Journal of Building Acoustics, 1(2), pp.125-136, 1994.
6. S. M. DANCE, Ph.D. Thesis, South Bank University, 1993
7. M. HODGSON, 84(1), pp.253-261. 1988

8. J. KANG, Acustica, 82, pp.509-516, 1996.
9. C. JONES, Ph.D. Thesis, South Bank Polytechnic, 1990.

Figure 1. The recording studio showing the source and receiver positions and the room surfaces

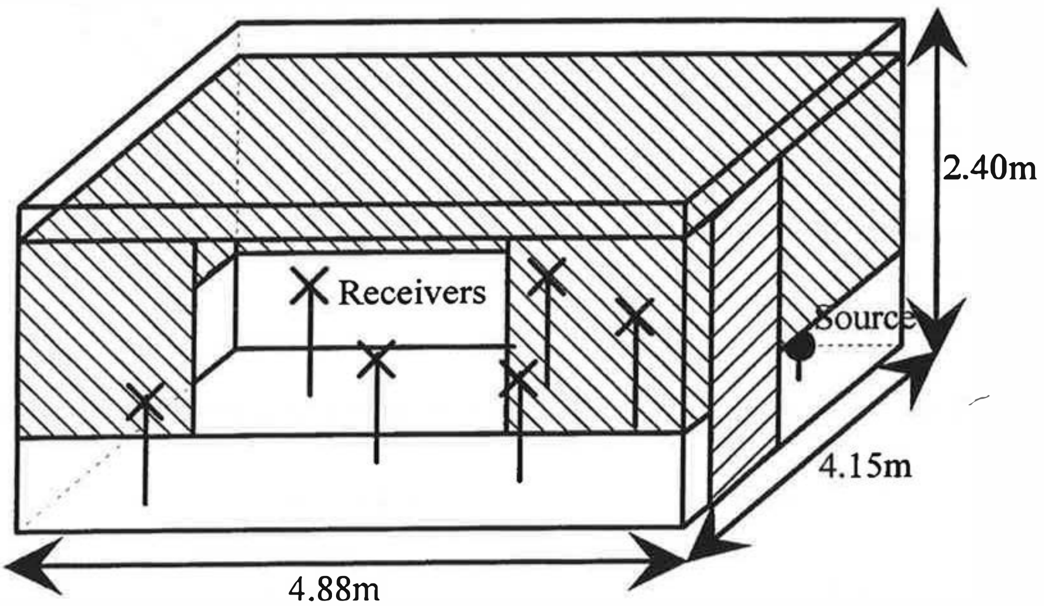


Figure 2. The measured and predicted RT in the recording studio for the 1 kHz octave band

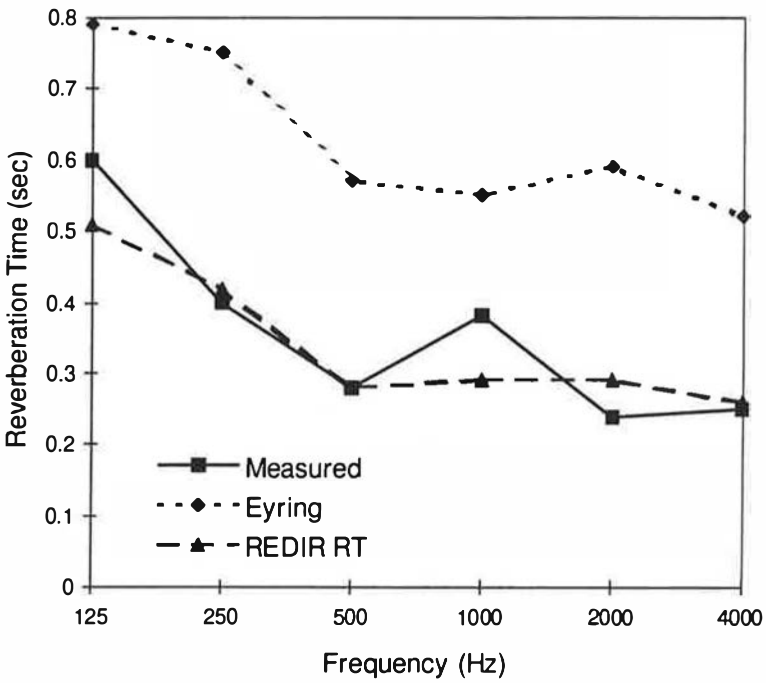


Figure 3. An illustration of the concert hall with the source and measurement positions

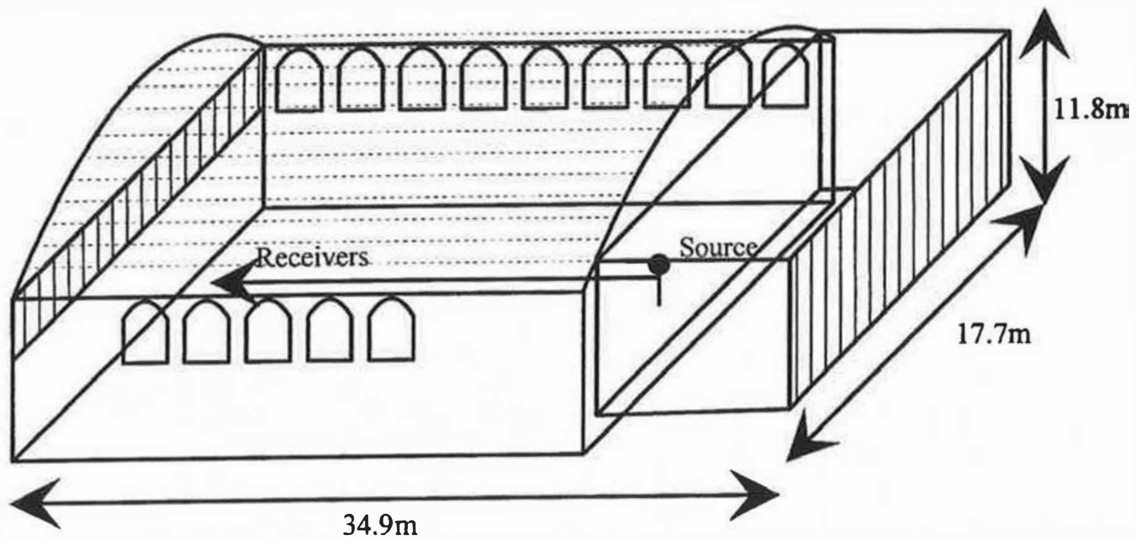


Figure 4. The measured and predicted RT and EDT for the 1 kHz octave band in the concert hall

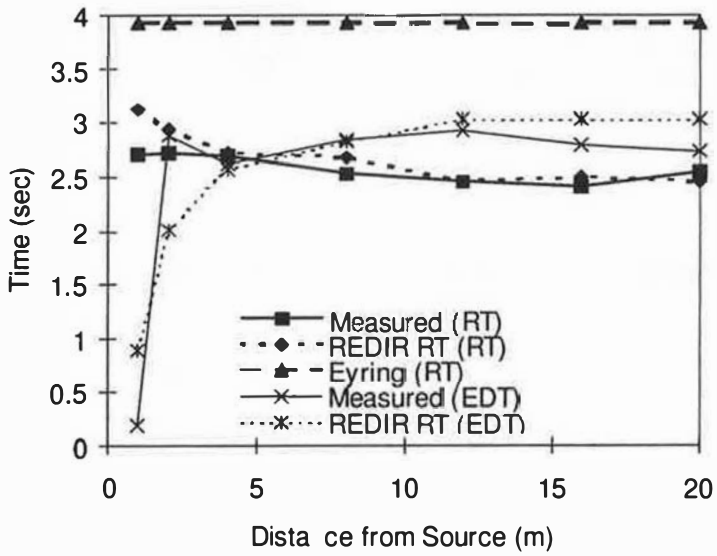
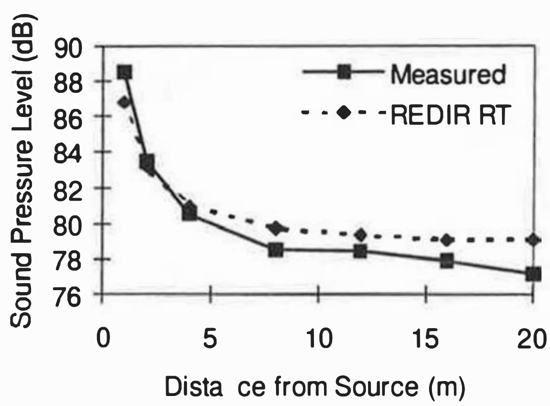


Figure 5. The measured and predicted SP for the 1 kHz octave band in the concert hall



Achieving relevance through facilities management

P. Barrett and M. Sexton, University of Salford[1]

Abstract

For a building to be sustainable it must have an economically viable role to play in society. To achieve this it must add value to the operations of those who use it.

Facilities management is thus focused on maximising the contribution of an organisation's built infrastructure to its core business (and usually crosses over into support services as well).

Based on a detailed two and a half year project, involving close collaboration with industry, this paper will report findings that:

(a) Clearly identify the multiple interactions that must all be effectively managed if facilities management is to be successful.

(b) Set out a way in which continuous, strategically orientated, improvement in facilities management can be achieved.

This paper, will, therefore, put in context the more technical aspects of building management, by providing the link to the users' needs in both the short and long term.

Introduction

Improving the environmental performance of buildings is becoming increasingly important for all of the stakeholders involved in the use of buildings. Efforts to achieve improvements, however, often centre around enhancing the environmental efficiency of buildings through fragmented, 'end of pipe' solutions. For example, installing energy efficient heating and ventilation systems in a building which, owing to its poor design, is inherently poorly insulated. It is argued that there is a need to expand the 'sustainability of buildings' debate to include the utility of buildings to those who use them. The environmental performance of buildings should not be assessed in isolation. For example, is it sustainable to have a very environmentally friendly office building which does not satisfy the needs of its occupiers? If progress is to be made towards truly sustainable buildings, a more holistic perspective needs to be taken which integrates the environmental performance of buildings within the guiding context that buildings have an economical role to play, and this can only be achieved by maximising the value of buildings to those who use them. Only once the economic utility of a building for its users has been established can the more traditional 'technical' environmental improvements have sustainable relevance.

This paper argues for the important role that facilities management has as a means to bring about this crucial goal of economic, user-focused management of buildings. The paper will be structured as follows. First, facilities management will be defined and discussed. Second, supple systems, a continuous quality improvement management approach, will be described as a fruitful framework to bring about effective and efficient facilities management. Finally, conclusions will be drawn.

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Facilities management

What is facilities management?

Facilities management is a rapidly emerging organisational discipline which aims to continuously enhance the contribution of a firm's facilities and supporting services to its overall competitiveness. Like most developing disciplines, facilities management has been, and continues to be defined in many ways. We would say that facilities management is:

"A strategically integrated approach to maintaining, improving and adapting the buildings and supporting services of an organisation in order to create an environment that strongly supports the primary objectives of that organisation"

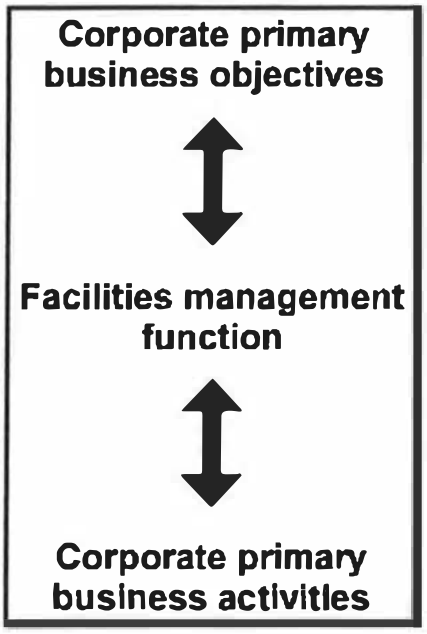


Figure 1: Relationship between the facilities management function and the corporate primary business

In essence, as shown in Figure 1, the *facilities management function* provides work environments to support the channelling of the firm's *primary business activities* towards the accomplishment of the firm's *primary business objectives*. An accountancy firm's primary business, for instance, is considered to involve all organisational objectives and activities relating to directly providing a professional accountancy service offering. In contrast, the accountancy firm's *secondary business* consists of those organisational areas which do not directly contribute to the accountancy service offered, but are nevertheless crucial.

An increasingly important secondary business activity, which is of relevance here, is the need to improve the environmental performance of a firm's buildings. This trend is in response to the need to reduce the energy costs of buildings, to conform to environmental, and health and safety legislation, and to develop the level of social responsibility expected of all firms from a wide range of publics.

The need for a strategically integrated approach to facilities management

At present corporate management often treats facilities management as a passive, low level cost centre which does not have the potential to add significant value to their primary organisational activities. However, the findings of a rigorous and wide-ranging two and a half year collaborative project undertaken in the Research Centre for the Built and Human Environment at the University of Salford, indicates that progressive firms are developing a clear link between primary and secondary business objectives, enabling high-value facilities management activity of strategic importance within their organisations. [1] By having this integrated approach, the facilities management function is able to carry out its secondary activities in support of primary activities in a strategically directed and consistent fashion. This integrated approach to facilities management is shown in Figure 2.

Without a strategically integrated facilities management presence, organisational energies will be reactively dissipated between both primary and secondary objectives and activities - to the detriment of all.

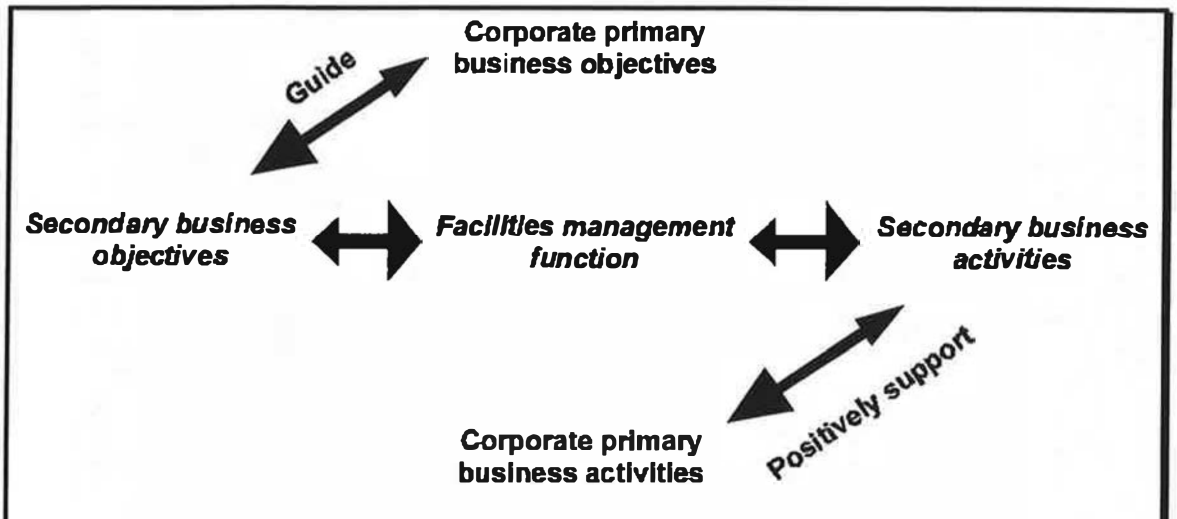


Figure 2: A strategically integrated approach to facilities management

Bringing about strategically integrated facilities management

The key to improving the economic, social and environmental performance of buildings is to introduce multiple, balanced feedback mechanisms so that organisations actually learn from occasions where they could have done better or from opportunities / ideas from other sources. This learning process is afforded by organisations creating the capacity to scan, sense and monitor significant aspects of their internal and external environments, the ability to link the resultant information to other information concerning the operating norms which direct activities, the ability to detect deviations from these norms; and the ability to initiate corrective action when deviations are detected. Furthermore, the feedback loops should be positively orientated in order that the organisation has the capacity to progressively improve through continuously learning; rather than a negative orientation which is geared towards the (eventually stagnating) maintenance of the prevailing organisation.

In terms of environmental performance, the feedback mechanisms encourage desirable *opportunity* based improvements (for example, proactive environmentally-conscious design), rather than generally ineffective and inefficient *crisis* management of problems areas (for example, installing emissions control equipment on inherently polluting boiler plant). An indication of the multiple linkages to inform and stimulate these improvement initiatives is given in the appendix to this paper. The model there was derived within the project, through multiple case study analyses.

In simple terms, the organisation collects feedback externally, as well as internally, then analyses the information and integrates it back into future service provision in order to improve performance levels. It should be stressed that the process is iterative and thus encourages continuous improvement. The concept is shown in diagrammatic form in Figure 3. which gives the International Organization for Standardization's Quality Management Loop for Services drawn from ISO 9004-2.[2] The feedback mechanisms occupy the lower half of the diagram. Based on this sort of thinking, and aiming for systems which are strategically focused, client-responsive and facilitate a continuing cycle of improvements, an approach has been developed, through debate and observation, which endeavours to meet these criteria. The approach has been styled "supple systems" and is discussed next.

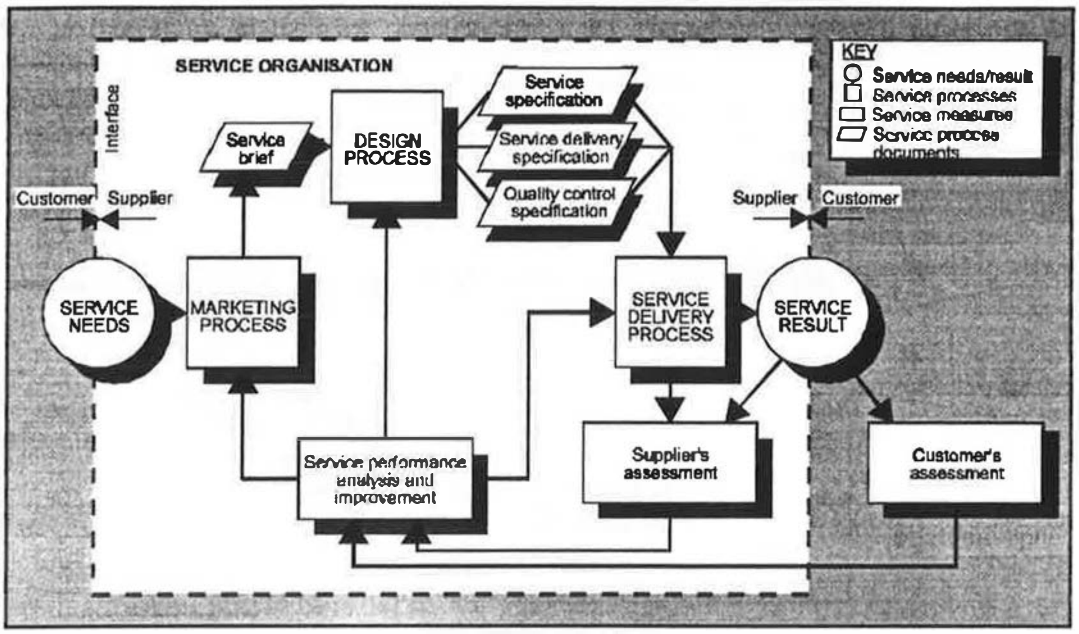


Figure 3. - Service quality loop

Supple systems

The supple systems approach originated from the construction quality management domain [3], but can be fruitfully enlarged and refocused towards the continuous quality improvement within organisations in general. The key features of supple systems are given in Table 1. There is insufficient room in this paper to consider each aspect in detail. However, in summary, the approach advocates that a strong, but flexible *audit* system is developed which ensures that improvements in the quality of the service are being achieved. The audit system identifies sources of feedback, assesses if action is required, and at what level, prioritises between alternatives, allocates responsibility, checks later that action was taken, tries to objectively assess the impact of the actions and finally feeds these findings back to those involved.

Table 1. - Key Features of Supple Systems

Feature	Description
Objective-nested	The systems are aligned to, and positively support, the planning, co-ordination and control of appropriate strategic organisational objectives. Systems should not be developed within an operational/technical vacuum.
Client / Stakeholder orientated	The systems are tested against stakeholder, and especially client requirements by actively seeking feedback through both hard and soft data.
Minimalist / Holistic	"As much as you must, as little as you may", that is, not having systems for their own sake, but rather targeting high risk / gain areas. Better to have made some progress on all important fronts than to have patchy provision.

Table 1 Continued. - Key Features of Supple Systems

Feature	Description
Loose-jointed	The systems operate at an audit level: clarifying objectives, checking performance and integrating efforts. At an operational level different styles and approaches can be accommodated, especially when they have proved themselves over time.
Evolutionary	Allow incremental and continuing progress to be made from whatever base.
Symbiotic with social systems	Build on the norms and culture of the organisation, for instance allowing self-control or group pressure to operate where appropriate.

Subsequent work on the nature of "quality" in buildings and construction has resulted in a formulation that considers it to comprise elements of: function, aesthetics, cost, time(liness), health and safety (internal environment), environmental performance and location. Various stakeholders have differing levels of interest in each of the specific factors and a diverse range of mechanisms exist through which they are controlled. For example, Fire Regulations for aspects of health and safety administered by the Local Authorities. Beyond this perspective it is interesting to note that the service industry literature stresses the importance of *how* services are delivered as well as what is done. It should be apparent from even brief consideration of these various factors that a wide-ranging, but strongly integrative approach is needed

Conclusion

The 'supple' approach to facilities management is a powerful means for organisations to inject greater relevance to the more technical aspects of building management, including environmental performance, by linking them to the overall strategic direction of the organisation. However, these strong synergies will only be developed if corporate managers view facilities management as being a valuable means of making a positive contribution to the primary business. The development of a successful facilities management competency, therefore, requires both corporate and facilities managers to fundamentally integrate primary and secondary objectives and activities.

Specifically, organisations will not be able to capture the holistic organisational meaning of sustainability issues if they have no appropriate net to catch them in. Supple systems can provide an integrated, developmental net which can provide positive benefit to organisations, however small, to do something, start somewhere, in what will become a continuous development in the capability to identify and satisfy, amongst others, progressively demanding environmental requirements.

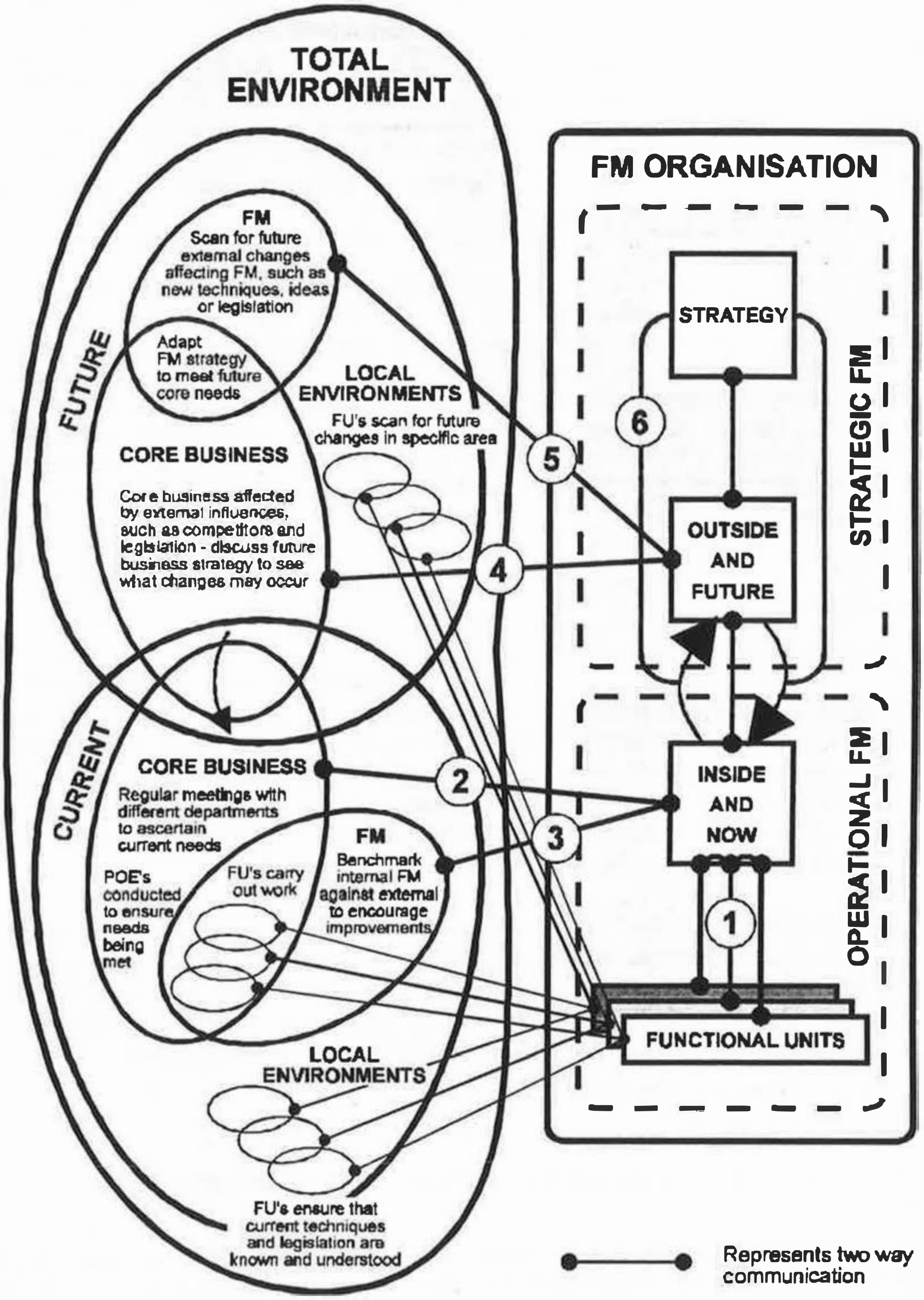
References

[1] Barrett, P. (Ed.), (1995), **Facilities Management: Towards Best Practice**, Blackwell Science: Oxford.

[2] ISO, (1991), **ISO 9004-2: Quality Management and Quality System Elements Part 2: Guidelines for Services, International Organization for Standardisation**, via British Standards Institute: London, as Part 8 of BS 5750.

[3] Barrett, P. (1994), 'Supple Systems for Quality Management', **RICS Research Paper Series**, Vol 1, No4, RICS, London.

Appendix: Generic Facilities Management Model [1]



Measurement and CFD modelling of room air flows

B Vazquez, P Haves, J J McGuirk & V I Hanby, Loughborough University[1]

Summary

The principal aim of the project is to investigate the interaction of the upward and downward buoyant plumes encountered in displacement ventilation and "chilled-beam" cooling systems. At present, it is unclear whether the cold plumes from chilled beams mix at high level, cooling the exhaust air rather than the space, or whether they penetrate into the occupied part of the space, cooling it but also recirculating pollutants and hence reducing the enhanced ventilation effectiveness that might otherwise have been obtained with displacement ventilation. The goals of the project are (i) to use experimental measurements to characterise the mixing of buoyant plumes and (ii) to validate different CFD turbulence models for use in this application.

Introduction

The commitment to stabilise CO_2 emissions and reduce the use of ozone-depleting refrigerants has focused attention on alternative methods of conditioning occupied spaces in buildings. In buildings where the need is predominantly for cooling rather than heating, the combination of static cooling and displacement ventilation has the potential to avoid or reduce the need for refrigeration systems with the corresponding benefits in terms of energy consumption and improvements in the quality of the indoor environment [1,2,3]. A form of static cooling that has significant cost advantages over radiant panels is the "chilled beam", which consists of a ceiling-mounted fin-tube heat exchanger through which air circulates by natural convection (Figure 1).

The project involves the study of the behaviour of chilled beams and displacement ventilation using both numerical methods (CFD) and experiments in a full scale test chamber. The research is focused on the interaction of the descending plumes of cool air from chilled beams with the ascending plumes that form above localised heat sources. The literature includes the results of measurements and model of unconfined single and multiple plumes, as found in displacement ventilation systems in the absence of static cooling [4,5,6]. There is also some published work on the interaction of radiant chilled panels with displacement ventilation systems [7,8], but there appears to be little or no detailed work reported on the interaction of chilled beams with displacement ventilation.

Experimental set up and equipment description

An experimental chamber measuring approximately 2 m x 2 m x 2.5 m, containing a cylindrical heat source and a chill beam, has been designed and constructed (Figure 2). The chamber represent a part of the actual room (see dotted line in Figure 1). The walls are made of perspex in order to allow both flow visualisation using a laser light sheet and detailed quantitative measurements of velocity and turbulence using a laser-Doppler anemometer. Laser-Doppler anemometry (LDA) is a non-intrusive technique that has been used widely to measure mean flow and turbulence characteristics for a large number of diverse flows. LDA has a number of advantages over probe-base methods such as the hot-wire anemometry. For example, the flow direction can be determined without ambiguity, no calibration is needed, measurements of the velocity components are independent of pressure and temperature gradients inside the test enclosure and high spatial and temporal resolution can be achieved. Disadvantage include high costs and the need to seed the flow with small, reflective particles.

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Figure 1 Chilled beam and Displacement ventilation

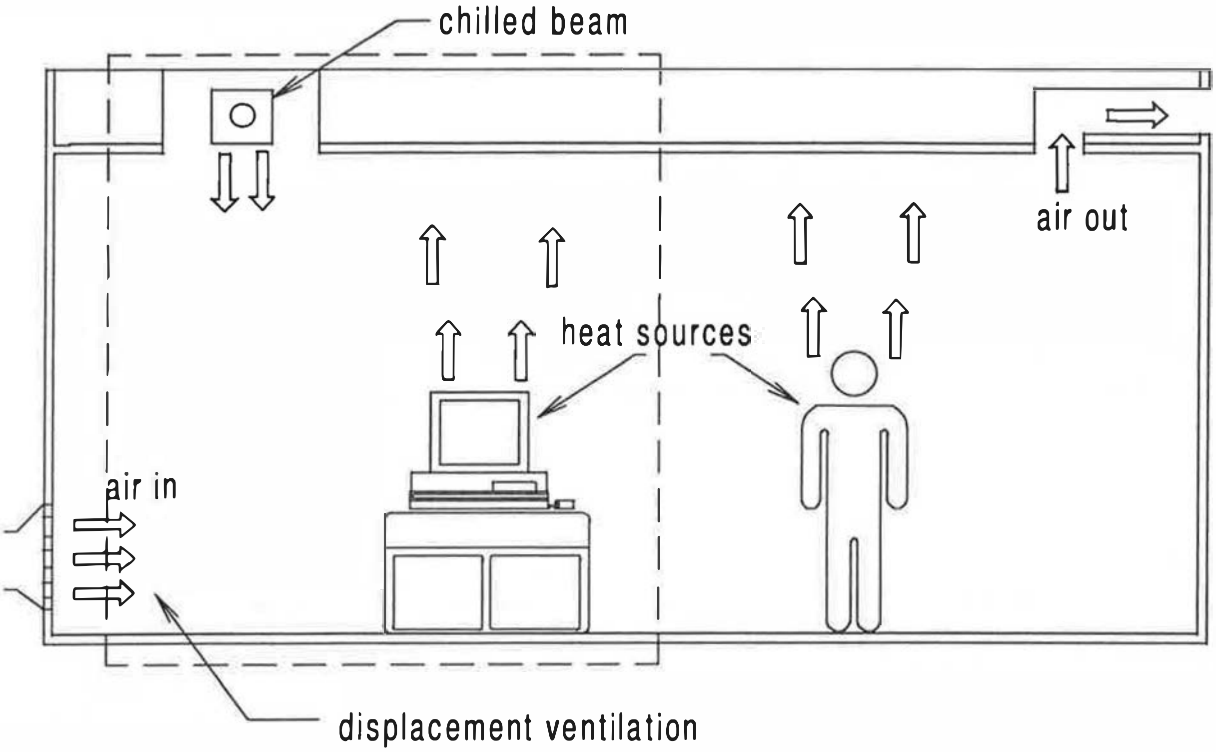
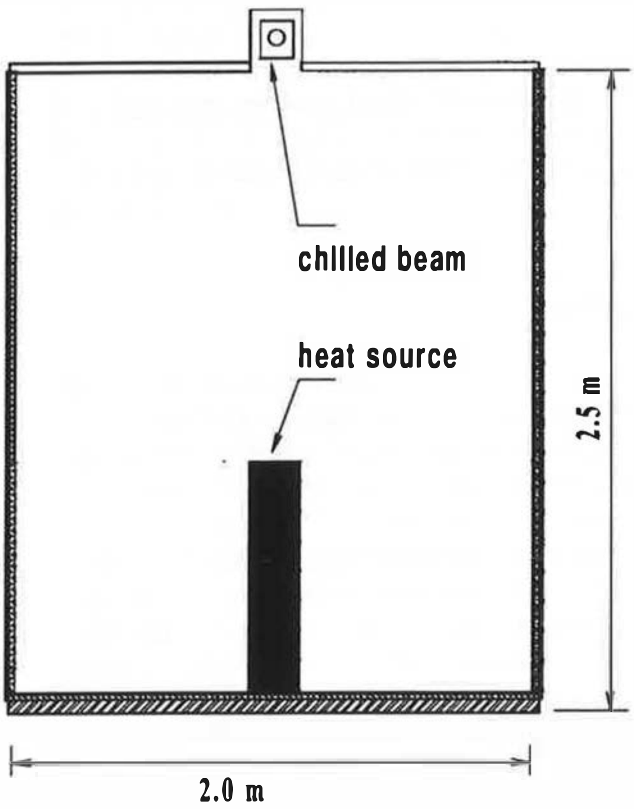


Figure 2 Experimental test chamber



The principle of the LDA technique involves the measurement of the variations in the intensity of the light scattered by moving particles traversing a fringe pattern generated with laser light. This fringe pattern (Figure 3) is formed when two laser beams of equal intensity intersect. The intensity of the light scattered by each seeding particle varies as it traverses the fringe pattern. The light scattered by the moving particles is collected by a photomultiplier. The voltage from the photomultiplier is then Fourier transformed in the signal processing unit. The frequency of the modulation in the intensity of the scattered light is proportional to the component of the velocity of the particle perpendicular to the bisector of the angle between the 2 laser beams (i.e. in the y direction in Figure 3). The ambiguity in the velocity direction is resolved by imposing a known frequency shift in the light in one of the beams, causing the fringe pattern to move. The frequency shift is chosen to be sufficient to make the fringe pattern move faster that any part of the flow. The velocity of the flow relative to the fringe pattern then always has the same sign, removing the ambiguity.

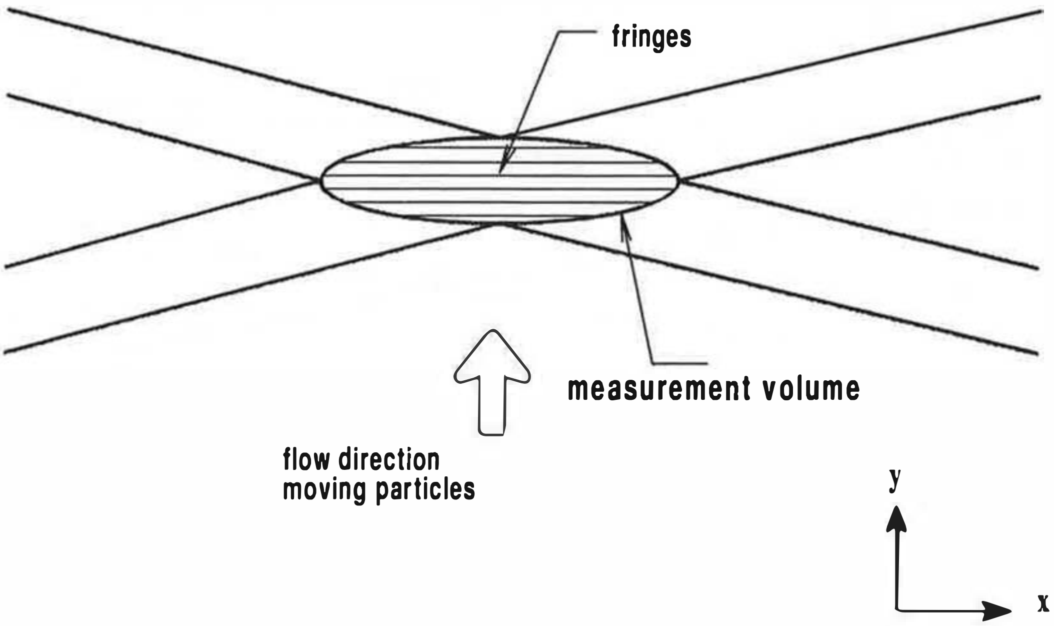


Figure 3 LDA measurement volume

Figure 4 shows the configuration of the laser Doppler anemometer. The optical subsystem consists of a 4 watt argon-ion laser, a ten meter long fibre optic cable and an optical probe. The optical probe is mounted on a motor-driven traverse that can cover a two dimensioned grid 600 mm by 1000 mm to an accuracy of 0.1 mm. The temperature inside the chamber is measured by 48 copper-constantan thermocouples. The temperature field in the interaction region will be measured by means of a small thermocouple (size 0.05 mm) with a response time of 0.05 sec, capable of registering the rapid temperature fluctuations associated with turbulent mixing. The small temperature probe will be positioned within 1 mm of the LDA measuring volume so that the measuring volume and the thermocouple will be in the same turbulent eddy. Measurements will be made of the velocity and temperature fields, including their turbulent fluctuations, in the region of interaction of the two plumes and in the boundary zones (hot source, chilled beam).

Measurements of the temperature distributions near the sources of the plumes and of the enclosure surface temperatures will be used as boundary conditions for CFD simulations of the flow inside the chamber. The measured velocity fields will be compared with those predicted using different turbulence models in the CFD simulations in order to determine the suitability of the different models for use in this type of application. Depending on the nature of the differences between the measurements and the CFD predictions, modifications will be made to one or more turbulence models in an effort to maximise the ratio of accuracy to computational effort for this type of problem.

The study will consider variants of both the $\kappa-\varepsilon$ and the Reynolds stress turbulence models and will also consider various discretisation schemes.

Preliminary tests

Preliminary tests were carried out in order to characterise the descending plumes formed by chill beams and the ascending plumes formed by hot sources (humans, electric equipment, etc.). 24 omni-directional probes were used to record the temperature and the velocity for different test cases. Flow visualisation tests showed strong air flow recirculation where the plumes interacted. The flow is unsteady, and reversals of the flow direction inside the interaction zone were observed. An LDA systems was then considered to be necessary to be able to measure the air velocities when reversals of flow direction are present.

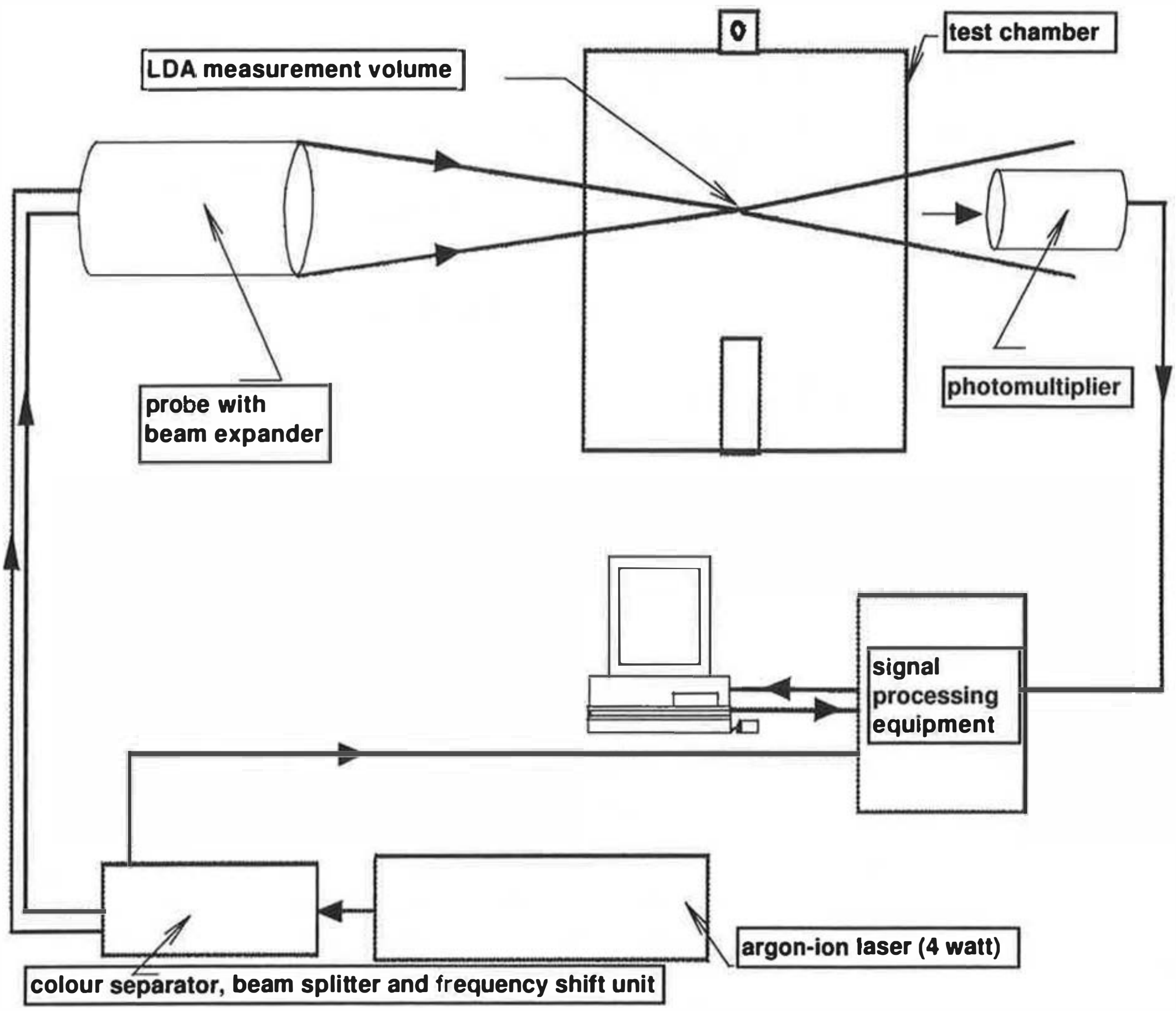


Figure 4 The LDA system and traversing equipment. The actual LDA system is configured for back scattering. Forward scattering is shown here to avoid an overly complicated diagram.

Conclusions

It is anticipated that this research will lead to further investigation using full-sized rooms and will ultimately be incorporated into design procedures and performance analysis methods for low energy cooling systems in buildings. The measurements will be obtained from a chill beam, but the work should have wider application, both to turbulence modelling and to the design and modelling of enclosed spaces in which buoyancy effects are important.

The work is designed to make significant contributions to the validation of turbulence models for use in the simulation of buoyant flows and support the evolution of CFD codes for room air flow applications.

References

[1] M Stahl and G M Keller. "A new development in air conditioning". *Transactions of the American Society of Heating, Refrigerating and Air-conditioning Engineers*, 98, Pt. 1. 1992.

[2] P J Jackman, "Displacement ventilation". In *Proceedings of CIBSE National Conference*, Canterbury, UK April 1991.

[2] T Wyatt. "Chilled beams and displacement ventilation" *CIBSE Journal*, November 1991.

[4] S Mierzwinski. "Testing and modelling of thermal plumes in rooms" In *Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness*. Tokyo, Japan, 1992.

[5] V Shankar, L Davison, and E Olsson. "Ventilation b displacement: calculation of the flow in vertical plumes". In *Proceedings of ROOMVENT'92*, Aalborg. Denmark, 1992.

[6] E Mundt, "Convection flows above common heat sources in rooms with displacement ventilation". In *Proceedings of ROOMVENT'90*, Olso, Norway, 1990.

[7] J Niu, "Modelling of cooled-ceilings Air-conditioning systems". PhD thesis Delft University of Technology, Netherlands, 1994.

[8] "Chilled Ceiling and displacement ventilation", CIBSE Wedneday 12 October London, 1994.

HVAC system simulation: modelling the performance of boilers

V I Hanby and G Li, Loughborough University[1]

Summary

This paper describes a two-year research project, funded by EPSRC grant GR/J65259, with the objective of developing an enhanced boiler model for use in HVAC system simulation. The model is expected to be able to predict emissions like *NOx*, *CO* and *SOx*, together with a detailed analysis of thermal performance for both gas- and oil-fired boilers.

A one-dimensional frame work was adopted, using a two-pass calculation procedure where appropriate, together with an hierarchical approach for some aspects. The thermal performance of the boiler was derived from basic heat transfer relationships, thus minimising the dependence on experimental data from boiler tests. The emissions of the major gaseous pollutants were calculated from both first-principle and empirical relationships.

The model was developed in the context of sectional type triple pass or shell-and-tube boilers with outputs in the range 100 kW -- 3 MW. Special features such as internal and external flue gas recirculation were considered.

The model provides good prediction of heat transfer performance and reproduces the values and trends of emissions throughout the operating range of the device. The usability of the model in HVAC simulation has been demonstrated by including first-order dynamics, writing it as a TRNSYS TYPE and incorporating it in an example system simulation.

Introduction

The fossil fuel-fired boiler is one of the most significant components of primary plant in view of its energy consumption and contribution of emissions to the environment. However, such significance has not been reflected in the rigour and functionality of current boiler models. The early models incorporated in HVAC system simulation programmes were typically empirical ones based on curve fits of operating efficiency against load. Besides their strong dependence on experimental data, there was minimal representation of the processes within the component and little or no attention was paid to the modelling of emissions. The alternative approach has been CFD simulation. The ability to conduct two- or three-dimensional analysis of a flow field in combination with some chemical reactions has, in recent years, led to a significant usage of CFD codes to analyse the performance of boilers and furnaces. However, the high computational intensity prevents the CFD simulation from being a viable way of enhancing the functionality of boiler models in building/HVAC plant simulation programs.

This study was aimed at developing a boiler simulation model which combines features of both approaches: to provide representation of the combustion characteristics such as *NOx*, *SOx* and *CO* emissions, together with a more detailed modelling of heat transfer processes without incurring a computational overhead which would prohibit their use within HVAC system simulation programs.

Description of the modelling approach

The modelling schema is illustrated in Fig. 1. The one-dimensional model consists of three major components: an adiabatic flame zone, a combustion chamber and a conventional heat exchanger section.

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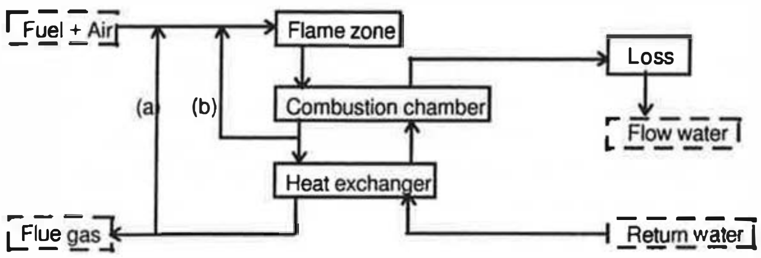
Losses to the environment from the water jacket are modelled as a simple subsidiary heat exchanger.



(a) External flue gas recirculation (b) Internal flue gas recirculation

Figure 1: Flow diagram of boiler model

Component model

The combustion process is assumed to be completed in the adiabatic flame zone. Taking account of dissociation at high temperature, the output of this zone is considered to be an equilibrium mixture at the corresponding flame temperature. In calculating the equilibrium composition of combustion products, The Newton-Raphson iteration method is used to solve a group of chemical equilibrium and conservation equations to provide the equilibrium composition of combustion products.

The combustion chamber and main heat exchanger were modelled as two counter flow heat exchangers using conventional *effectiveness-NTU* method. A `once-through' modelling algorithm was used as the basic framework, keeping any iterative loops to a minimum. An iterative algorithm was set up to deal with internal or external flue gas recirculations.

An important feature of this work was to substitute first-principle heat transfer algorithms, combined with basic geometrical and flow data for the boiler, for global (*UA*) values derived from testing programmes. Since the combustion products enter the combustion chamber at very high temperature, heat transfer was calculated separately for convection and radiation. As no suitable correlation was found for evaluating the combustion chamber gas side convective heat transfer, off-line CFD prediction was performed, using the CFX-F3D code [1], over a range of boiler combustion chamber geometry and flow conditions. This provided the heat transfer data which then led to the generation of an empirical equation for the boiler modelling approach.

Emission models

<u>*NOx* formation:</u>

There are three recognised routes for the formation of *NO* in the combustion process:

1. *prompt NO* is formed early in the flame, and is influenced by the availability of the *CH* radical;
2. *thermal NO* is formed under conditions of high temperature and the availability of free oxygen --- this is described by the well-known Zeldovitch non-branching chain reaction [2];
3. *fuel NO* is formed from nitrogen chemically-bound in the fuel.

In this study only the first two mechanisms were considered as the formation of fuel *NO* occurs only in installations burning solid fuel and residual fuel oils: these were considered to be outside the scope of this study.

Two approaches were evaluated in this research: a one-dimensional first principle model for gas-fired boilers, based on integration of the relevant chemical kinetic equations, and a fully-empirical model which was applicable to both gas- and oil-fired boilers.

In the case of the first principle model, a two-step combustion reaction mechanism [3] was solved for a finite time step of 1 microsecond. This enabled the calculation of the formation of prompt *NO* to be carried out. A temperature of 500 ^{o}C is necessary to trigger the combustion reactions and the reaction is `ignited' by assuming upstream heat transfer from the flame. As the combustion products tracked downstream through the combustion chamber and main heat exchanger the Zeldovitch rate equation was used to calculate thermal *NO* formation.

The alternate modelling method, applicable to both oil- and gas-firing, was based on an empirical equation in the form of

$$ln\left(\frac{NOx}{O_2}\right) = m\left(\frac{10000}{T_f}\right) + c \qquad (1)$$

where *NOx* is the *NOx* concentration (ppm wet), O_2 is the volume percentage of free oxygen in the flue gas (% wet) and T_f the adiabatic flame temperature (K) calculated for the operating conditions of the boiler. The regression constants *m* and *c* were evaluated for oil- and gas-firing respectively from experimental data [4].

This approach has the advantage of computational simplicity; also, it provides reliable prediction for the *NOx* formation over the normal range of boiler operation conditions. However the drawback is, for stoichiometric or rich combustion, equation (1) predicts no *NOx* as the residual oxygen tends to zero. In addition, it does not predict the change of *NOx* formation with firing rate, since the flame temperature and the concentration of residual oxygen are independent of the firing rate.

CO formation

The most significant influences on the formation of carbon monoxide in the flue gases are imperfect mixing of the fuel and air (properties of the burner head) and rapid quenching of pockets of combustion chamber gas near cool surfaces (determined by the dimensions of the combustion chamber). It is not feasible to describe these effects deterministically in a one-dimensional model, hence an empirical approach was used.

The basis of the approach was the equilibrium value ($[CO]_e$) at the mean combustion chamber temperature corrected for the relative sizes of the flame and the combustion chamber. Consideration of boiler test data produced a relationship of the form

$$[CO] = k_1 k_2 [CO]_e \qquad (2)$$

for a given design of burner head. k_1 and k_2 are the correction factors for the geometrical configuration of the combustion chamber and the combustion chamber intensity respectively.

SOx formation

Emissions of sulphur oxides can be significant in the case of oil-fired boilers: these take the form of SO_2, SO_3 or sulphuric acid vapour. *SOx* emissions were taken to be the local equilibrium values of the system

$$SO_2 + \frac{1}{2}O_2 \Leftrightarrow SO_3 \qquad (3)$$

at the flue gas exit temperature.

Performance of the model

Stand-alone mode

The initial testing of the model was carried out by running the model in stand-alone mode. The objective of this was to ascertain the extent to which the model could predict absolute values and performance trends.

An example of the comparison of the predicted global performance of the boiler with experimental data for triple-pass gas- and oil-fired boilers obtained from a commercial testing programme [4] is shown in the Table 1. The test figures were obtained with the boiler operating at its rated input (190 kW), a water return temperature of 71 ^{o}C and a flow temperature of around 82 ^{o}C. The excess air ratio was the measured value for the specific test cases.

Performance	Gas- firing Excess air ratio=1.22		Oil- firing Excess air ratio=1.26	
	Predicted	Measured	Predicted	Measured
Output(kW)	185.5	190.0	188.8	190.0
Net efficiency(%)	89.2	91.4	90.7	91.3
Flue gas temperature(^{o}C)	195.0	172.0	161.8	172.0
NOx (ppm wet)	46.3	46.2	70.2	74.6
CO (ppm wet)	71.3	86.4	65.4	50.6
SOx (ppm wet)			116	not available

Table 1: Performance of triple-pass boiler for gas- and oil-firing

Thermal performance characteristics

Most commercial-size boilers operate under continuously modulated control or off/low-fire/high-fire control, both the air and fuel are modulated proportionately. As the fuel and air flow rates are reduced, the exit flue gas temperature should fall, with a corresponding increase in thermal efficiency. The residence time of the gases in the device gets longer, with a consequent increase in the `size' of the heat exchanger.

Fig. 2 shows that the model correctly predicts this trend as the firing rate (expressed as a fraction of the rated input) is reduced.

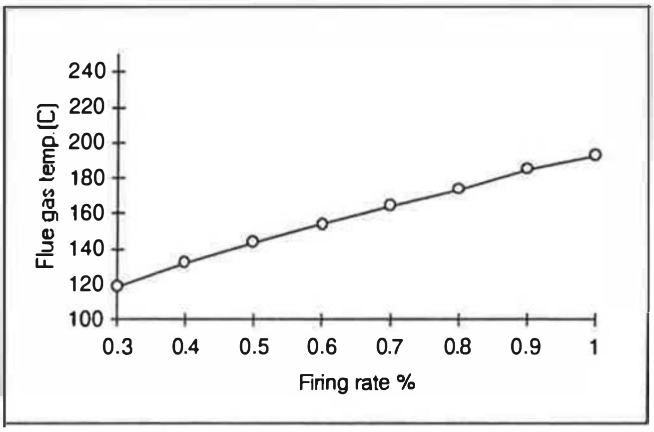


Figure 2: Variation of flue gas temperature with firing rate

First-principle NOx model

The formation of *NOx* is strongly dependent on temperature and more weakly affected by oxygen concentration. As excess air leads to a reduction in flame temperature it is well-known that a peak in *NOx* occurs on the lean side of the stoichiometric air-to-fuel ratio. The predicted *NOx* emissions from the prototype triple-pass boiler at its maximum firing rate over a range of excess air levels is shown in Fig. 3. A very strong peak can be seen at 2.5% excess air: typical operating conditions are within the range 15 - 25%.

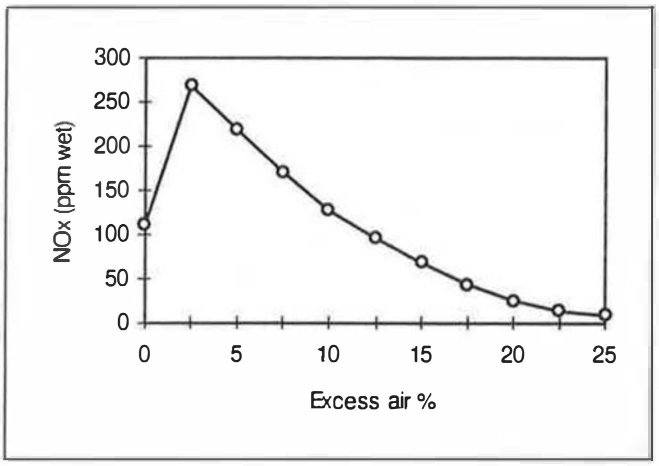
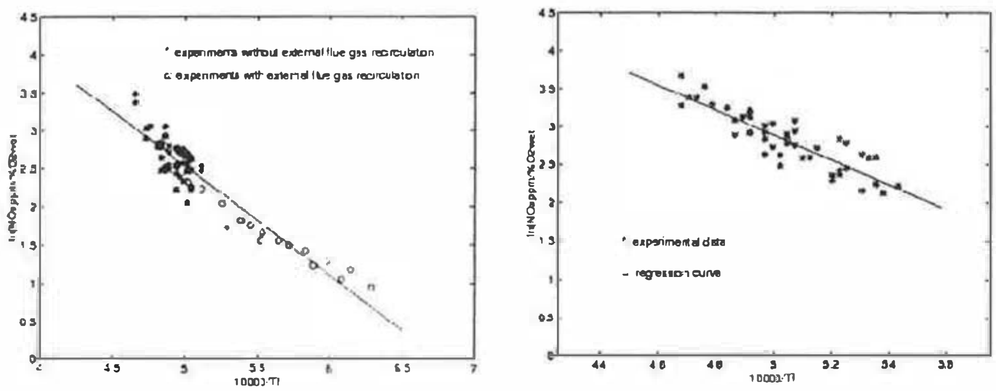


Figure 3: Prediction of *NOx* formation with excess air

The variation of *NOx* emissions with firing rate is dependent on burner design: For a typical blast tube burner, the curve is rather flat. At typical operational excess air levels the model predicts a slight increase in *NOx* levels as the firing rate is reduced.

Empirical NOx model

Two correlations were derived for the empirical model: one for gas-fired boiler/burner combinations and one for oil-fired units. The results are illustrated in Fig. 4 (a) and (b). This model also reproduces most of the operational characteristics of boilers under a variety of operating conditions but it would not be effective under near-stoichiometric combustion.



(a) Gas-firing (b) Oil-firing

Figure 4: Empirical correlation of *NOx* formation with experimental data

Incorporation into system simulation

To illustrate the potential of the model it was incorporated into a contemporary HVAC simulation program. The package chosen was TRNSYS 14.1 [6] as this is widely-used in both the USA and in Europe, where there is an active User Club. The TRNSYS TYPE consisted of 3 input variables, 7 output variables and 39 parameters. A simple subsystem was defined (Fig. 5) which enabled the boiler to be subjected to an arbitrary load pattern as a function of time.

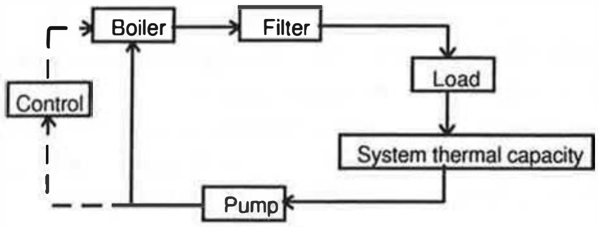


Figure 5: Boiler-load system

The prototype boiler modelled in this case was a gas-fired unit with a rated output of 190 kW [7]. The boiler has a two stage burner operating on high- and low-fire, controlled according to the required throttling range of the water flow temperature.

Two scenarios were modelled:

1. Start-up from an initial system temperature of 24^oC, with the thermal load assumed to be in proportion with *Tw*.
2. Operation with a fixed load of 170kW over a period of 4 hours. The magnitude of this load falls between the outputs of high- and low-firing rates of the boiler.

The results of TRNSYS simulation are shown in Fig. 6. In the start-up phase (Fig. 6 (a)), the water temperature and flue gas temperature in the system exhibit the expected first-order type time lag: this accords with the results of dynamic tests on this type of boiler [4]. When the constant load is imposed on the boiler, the cycling between low- and high-firing is evident. Fig. 6 (b) shows the variations in the water and the flue gas temperatures during this mode of operation.

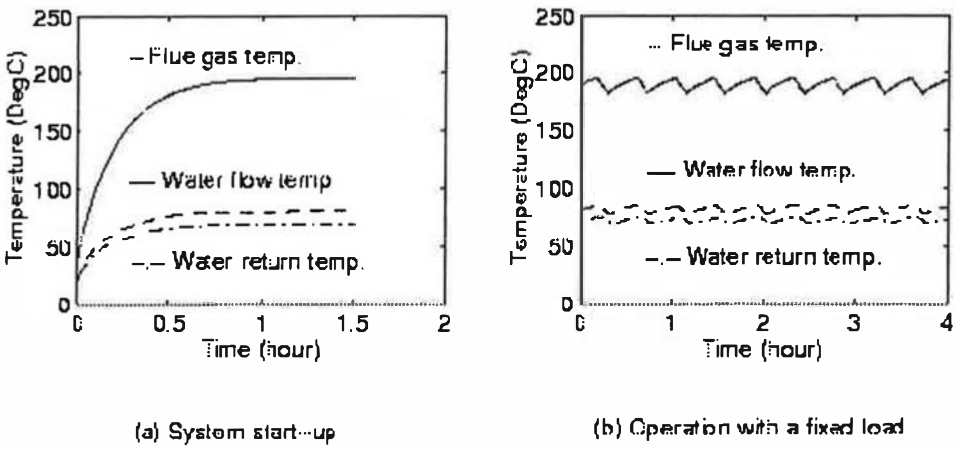


Figure 6: TRNSYS simulation results

The composition of the flue gas (including the *NOx* emissions) is predicted and also known experimentally to achieve a steady-state value immediately after start-up. The levels of *NOx* in the flue gas also respond to the changes in operating regime of the boiler, although the amplitude is quite small.

Conclusion

A three-component model to represent oil- and gas-fired boilers has been developed and implemented in a system simulation program. The model relies primarily on geometrical information on the combustion chamber and heat exchanger for the calculation of its thermodynamic performance, following the development of a suitable correlation for convective heat transfer in a cylindrical combustion chamber.

It was found that *NOx* formation could be calculated satisfactorily from established chemical rate equations in the case of gas-fired units, with separate consideration of the prompt and thermal routes. This approach is not feasible with liquid fuels. An empirical relationship based on the adiabatic flame temperature and the air-to-fuel ratio has been shown to work effectively over the operating ranges encountered for both gas- and oil-firing unit. A fully empirical model was found necessary in the case of carbon monoxide emissions due to the constraint of having to adopt a one-dimensional approach.

A comparison of the output of the model with tests carried out on commercial units has shown that the model has the capability to represent both trends and absolute values representing the thermal and emissions performance of such devices.

Acknowledgements

The authors wish to acknowledge the Engineering and Physical Sciences Research Council for financial support of this work and Dr Arnold Teekaram of the Building Services Research and Information Association for permission to quote data from the Commercial Boiler Emissions Project.

References

[1] AEA Technology, *CFX 4.1 User Guide*, (1995).

[2] Zeldovich, Y. B., *Acta Physicochem USSR*, **21**, p 557, (1946)

[3} Dupont,V., Pourkashanian,M. and Williams,A., ``Modelling Process Heaters Fired by Natural Gas," *J.Inst.Energy*, **66**, No. 466, 20-28, (1993).

[4] Teekaram,A. J. H. and Brown, R. G., ``Commercial Boiler Emissions," Draft Final Report 77520/4, BSRIA, Bracknell, UK, (1994).

[5] Teekaram,A. J. H., ``An Experimental Investigation into Flue Gaseous Emlsslons from Commercial Boiler Plants," BSRIA, Bracknell, UK. Private Communication (1995).

[6] *TRNSYS 14.1 Manual*, Solar Energy Laboratory, University of Wisconsin -- Madison, Madison, WI, USA (1994).

[7] Strebel Ltd.V, Camberley, UK. Product Information on RU1S-4 Boiler (1995).

[8] von Volkev Gnielinski, *Forschung a.Vd.V Geb.Vd. Ingenieurwes* , Band **41**, Nr 1, 7 -- 16, (1975).

[9] Foster,T., Dupont,V., Poukashanian,M. and Williams,A. ``Low-*NOx* Domestic Water-Heating Appliances," *J.Inst.Energy*, **67**, 472, 101-108, (1994).

[10] Heywood,J. B. *Internal Combustion Engine Fundamentals,* McGraw-Hill, New York, (1988).

[11] Rhine, J. and Tucker, R. ``Modelling of Gas-Fired Furnaces and Boilers,' British Gas plc, (1988).

[12] Li, G. ``Study of Convective Heat Transfer in Typical Cylindrical Combustion Chamber by CFD Simulation," Internal Report, Department of Civil and Building Engineering, Loughborough University. (1996).

[13] Holman, J.P., *Heat Transfer*, 6th Edition, McGraw-Hill Book Company (1986).

[14] Emerson, W.H., ``Shell-Side Pressure Drop and Heat Transfer with Turbulent Flow in Segmental Baffled Shell-and Tube Heat Exchangers," *J.Heat Mass Transfer*, **6**, 649-668 (1963).

Wind energy associated with buildings

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Summary

This paper discusses the wind energy which might reasonably be recovered by wind generators incorporated into the structure of buildings, without large impact on the exterior environment. Wind energy has been assessed for 3 generic types of high rise building in an urban environment, and 2 specific building designs in a suburban environment. 1:250 scale models have been analysed in wind tunnel tests using simulated natural boundary layers characteristic of the relevant wind environments. The measured power ratios, non-dimensionalised by the 50 metre wind speed, are combined with standard statistical wind rose data for different sites to give the ideal mean annual wind energy available for a given type of building and wind generator layout. A vertical axis wind turbine has been tested for a possible combination with building and a superior site and results obtained using the building power ratios and wind statistics to give annual mean wind energy estimates. The maximum energy available for a high rise building in a slightly above average UK city centre wind environment is up to 50% of the lighting load of a modern building. The possibility of using this power to enhance a natural ventilation system in the building are also discussed.

Introduction

There have been many recent initiatives to improve the energy efficiency of buildings, and as a result there is increasing interest in low or zero energy buildings. For the UK, wind energy is a possible source of non-grid supply and estimates of the quantity which might reasonably be captured by suitable turbines sited on a generic building in order to contribute to its essential energy requirement has been studied. The results indicate that the wind concentrating effect of a building can partially compensate for the much less favourable urban flow environment.

The paper describes an investigation of simple generic buildings in 2 basic categories:

- high rise buildings in city centre conditions
- a low rise building form of large length to width (to get a large roof area to building volume) in suburban conditions.

The wind energy flowing through areas within a practical capture distance of the building surface was measured. These areas were taken to be sited adjacent to the upper walls and roof of the high rise types of building and along the roof ridge of the low rise buildings.

Building and boundary layer models

City centre and suburban atmospheric boundary layers were simulated using a standard technique, involving upstream spires and barrier followed by a considerable fetch with roughness, in the department's 3m (wide) x 1.5m (high) wind tunnel. The procedure given by Cook [1,2] was used to calculate the scales and aerodynamic roughness lengths of these simulations and indicated very similar scale factors in both cases at just greater than 1:250, the scale factor used for the tests.

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Simple representative plan sections were selected for the buildings which were based on a constant plan area of 400m2 (thus enabling comparison on the basis of building volume or floor area). The standard high rise building was 20 storeys high with a storey height of 3.5m. The plan sections were round, square and 'twin round' (twin towers). The height of the round section model could be reduced to 14 storeys or increased to 28 storeys. Hot-wire anemometry was used to measure the velocities.

Initial velocity measurements revealed a highly turbulent region of low velocity just above the roof as expected, indicating that roof wind generators would have to be mounted well above horizontal flat roofs. Similar measurements were also made on a long low building in a suburban boundary layer, showing comparable but lower power densities. The remainder of this paper will concentrate on the results obtained for high rise buildings by siting generators in the areas adjacent to the upper (vertical) walls.

Simulation of wind generator / building interaction.

The effective resistance of operating wind generators may significantly affect the flow around the buildings. From consideration of the initial measurements of energy flux through areas surrounding the basic building shapes, it was decided that generators of 3m diameter and of the necessary vertical length (1/2 the building height was selected) sited at either end of a diameter would be a representative arrangement which could be used for the single tower city buildings, and of 6m diameter (to give the same wind generator area) for the gap in the twin tower building.

Measurements were then carried out using the 1/250 scale models, simulating the effect of the wind generators by woven wire mesh. This was done over the top 10 storeys only because of the lower velocities over the lower parts of the building. Measurements were made with the turbines sited 'free' but adjacent to the wall, simulated by a short width of wire mesh projecting from the building wall, and with each turbine running in a 'duct' between the building wall and a short length of shaped outer wall, simulated by a wire mesh across this duct. The ducted arrangement has the potential to give reduced noise levels and increased efficiency.

In order to ensure post-critical behaviour of the round buildings measurements were made with surface roughness and trip wires added. It was concluded that the relatively highly turbulent conditions of the incident flow ensured that the boundary layers on the building were turbulent and that transition promotion was unnecessary.

The effective wind power flux at a mesh is equal to:

$$\tfrac{1}{2}\rho k U^3$$

where k is the resistance factor of the mesh. Meshes covering a range of k were tried on each building to obtain the optimum k and wind direction for the highest power.

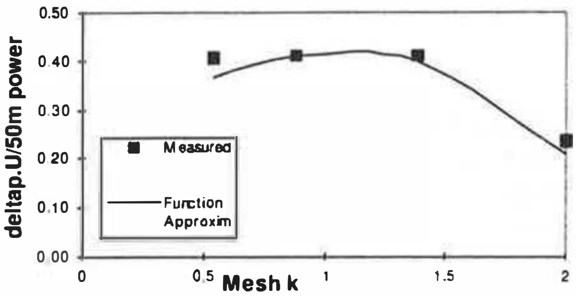

Fig. 1: Example power v flow resistance.

Fig. 1 shows the results for a particular long, quasi-two-dimensional building with the wind direction normal to it. The power flux is expressed as a ratio to that for the undisturbed wind at the reference height . The energy capture characteristics, which now include the effect of the building, have a relatively broad optimum indicating that a wind generator could be operated away from the optimum condition without significantly reducing the available power.

Measurements were then made to calculate the building response in terms of this power flux ratio to wind from all 360° in 30° sectors, since the published wind data uses these sectors [3]. Table 1 below shows the response for the round section building taking account of symmetry.

Building Ref: 20 Storey Round				
			Wind Environment: zo=	1.45 m
Power Factors ref. Uz-d=50m:			do=	24.5 m
Rel. Strys	11-15	16-20	WED dia (m):	3
Orntn. Ht:	17.5	17.5	Floor Area (m2):	8000
0/180	0.599	0.705	Cap. Region Base Ht (m):	35
30/150	0.385	0.330		
60/120	0.000	0.000	Local deltap/dyn.hd (k)	1.4
90/270	0.000	0.000		
210/330	0.396	0.508		
240/300	0.081	0.074		

Table 1: Example of building power factors

The angle is defined as zero when the wind is normal to the diameter containing the generators. The table also shows the characteristics of the boundary layer to which this strictly applies, and the resistance factor of the simulated wind generator. The power fluxes for the upper and lower sets of storeys in the (upper) section being considered are presented separately.

Ideal annual mean wind energy

The ideal annual mean wind energy associated with a particular geometry of building and wind turbine configuration can be obtained by combining the building response with the annual mean wind data as illustrated below. All wind data used has

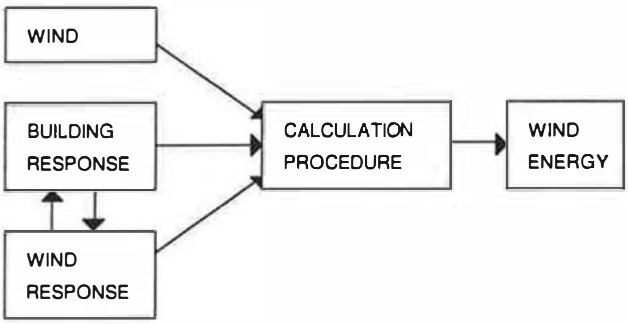

Fig 2: Diagram of calculation procedure

been taken from the European Wind Atlas [3], and adjusted to the required surface roughness. Four sites were assessed: Birmingham, Blackpool, London and Yeovilton.

The energy can be expressed in terms of mean annual energy per m2 generator area and, of more interest to building designers, per m2 building floor area (all storeys). Typical results are around 1/2 of the lighting load for a modern efficient building [4].

Of the high rise buildings tested, round planform, square planform, elliptic planform and twin round towers, the round section building was the second best high rise building section for energy capture giving just over half that of the twin towers in the Birmingham conditions.

The building orientation and wind data can be quickly changed allowing comparison of different regions and building orientations. Figure 3 shows the ideal annual energies for the twin tower building for 5 of the 6 basic orientations in 4 UK wind regions. As expected, of the 4 sites computed, Blackpool and Yeovilton are significantly higher than Birmingham, Yeovilton generally being higher except for the orientations taking advantage of the predominant onshore-offshore direction at Blackpool. This directional concentration effect also improves the relative performance of the single tower buildings and of the long low suburban buildings.

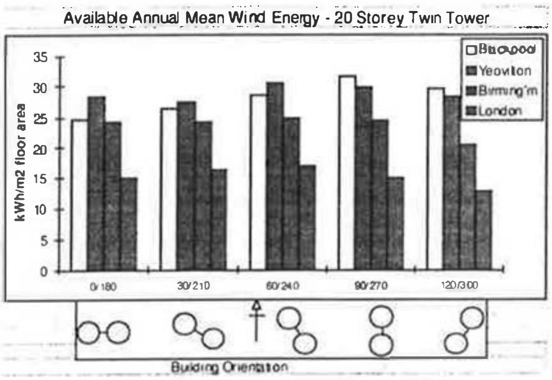

Fig. 3: Orientation & region comparison - 20 storey twin tower

These have relatively poor performance away from the best wind angles and noticeably greater variation of annual energy with building orientation in a direction concentrated wind environment. More details of these are given in [5].

Wind energy estimates including generator response

The vertical axis wind turbine (VAWT) is the more likely configuration to combine with the architecture of a building, the axis running parallel to the walls of tall buildings and horizontally along the roof ridge of long low rise buildings. Detailed power measurements have been made on a 1:15 scale model VAWT of the same solidity as that of Wilmer [6] to compare the performance between unconstrained operation, operation in close proximity to a building surface and operation under 'ducted' conditions.

The flow resistance in terms of the ratio of static pressure drop to dynamic pressure was also measured in order to set the equivalent resistance for the meshes on the 1/250 building models. Using these, the net result for the above twin-tower building sited at Birmingham is a total annual energy capture of about 3.5kWh/m2 floor area or about 2W/m2 during hours of office use.

The equivalent energy for a specific elongated building form in a suburban boundary layer was similarly found to be about 70 kWh per metre length of building. The energy per unit capture area is less than 20%

of that of the high rise building, thus the performance of long low buildings is relatively poor because of their being entirely in the lower wind environment.

Wind energy and natural ventilation

As part of the development of increasingly energy efficient buildings, natural ventilation has been widely researched recently as a means of minimising the power consumption of the air conditioning required for modern 'sealed' buildings. Natural ventilation which is often achieved through the use of wind scoops (roof mounted intakes facing into the wind) or various designs of wind-tower which are mainly, but not always, extractor devices using a low pressure effect from the wind, have a major limitation that they cannot generate a driving pressure much more than the dynamic head of the wind. This means that they are severely limited in their ability to overcome the pressure losses of a system incorporating ducting, heat exchangers and filters which are often desirable.

Wind generators offer a means of enhancing natural ventilation by capturing power at low density over a relatively large area and concentrating it to provide higher power over the smaller area of a typical ventilation inlet or exhaust. This may be done indirectly through an electrical generator, connection and electric fans or more efficiently by direct combination of the fan and turbine functions on the same piece of rotating machinery. This possibility is currently being investigated.

Conclusions

- Wind generators sited on a building can only make a small contribution to its energy requirements, the maximum level being less than 50% of the lighting requirement in slightly above average UK wind conditions.
- The main factors governing this are the low overall efficiency of the wind turbine and the limited siting area if significant increase of the building structural strength and planning concerns are to be avoided.
- Energy capture is enhanced when generators can be sited in a 'gap' between tall building blocks and a relatively bi-direction wind rose characteristic occurs.
- Noise and safety aspects, and vibration elimination have not been considered in this paper.

References

1 COOK N J, Designers guide to wind loading of building structures - Part 1. 1985, BRE

2 COOK N J, Determination of model scale factor in wind tunnel simulations of adiabatic atmospheric boundary layer, Journal of Wind Engineering, 1977/78, 2, 311-321

3 TROEN I, PETERSEN E L, European Wind Atlas, 1989, Riso National Laboratories

4 ENERGY EFFICIENCY OFFICE, Energy Consumption Guide 19 - Energy Efficiency in Offices, 1991, Department of the Environment

5 JENKINS N H A, GRAHAM J M R, Measurement and prediction of wind energy in association with buildings, Proceedings BWEA 17, University of Warwick, 1995

6 WILMER A C, The aerodynamic design and testing of a vertical axis windmill, Proceedings IEEE Conference on Future Energy Concepts, January 1979

Model-based solutions for full scale HVAC VAV systems

G S Virk, Portsmouth University[1], D L Loveday Loughborough University[2], D Azzi[1] and A K M Azad[1]

Summary

The paper considers the testing of a full-scale research facility, so that models, which assist and improve the operation of HVAC installations in office buildings, can be developed. Preliminary modelling results are presented and the models developed are used to predict temperature and humidity over different time horizons. Possible extension to other built environment applications are also discussed.

Introduction

The work described here is carried out under an EPSRC funded project, entitled 'The design of on-line models for multi-zone office air conditioning to aid commissioning and maintenance". The objectives of the project are:

(i) to develop and validate a self-commissioning model for a full-scale three zone test facility;
(ii) to assess the ability of the model to detect faults in the plant and changes to the building;
(iii) to assess whether a thermo-physical simulation can be used for model initialisation and sensor selection; and
(iv) to assess the potential of the model for control.

In this paper we concentrate the first objective, *i.e.* model derivation, and present some initial results obtained and their implication on future work.

Most of today's process management systems implement direct digital control techniques for effective operation of plant and systems. This has been made possible due to the widespread use of computers which allow simultaneous monitoring of multiple variables/actuators together with fast processing of the wealth of data this generates. However, the sophistication in computer hardware is rarely matched by the software or decision making mthodologies used in achieving the desired objectives. In the case of Building Management Systems, (BMS) controllers usually implement any variant of the well known PID scheme; here the error resulting from comparing the controlled output and the required set-point is fed to the controller which generates a signal made up of the error, its integral and/or (in a few cases) its derivative. This signal is then fed to the plant as the corrective control input. PID controllers have been found to be highly suitable for Single Input Single Output (SISO) applications or those which can be broken into a set of SISO sub-systems. In the case of multivariable systems, the standard PID controller does not normally work as effectively because it cannot cater for the multiple interactions present in the system.

The Building Services community has over the years begun to take on new techniques and produced improved control strategies to raise the state-of-the-art of air conditioning control. One such method is the Optimum Start/Stop (OSS) scheme which often comes as one integrated function with a BMS. This technique consists in firstly starting, say the heating in a building prior to the arrival of occupants to ensure comfort conditions at the start of the working day and secondly, stopping it sometime prior to the end of the working day to save on energy bills. Another innovative technique utilised in space conditioning is the variable air volume (VAV) scheme; this was introduced in the 70's as a solution to the problems occasioned by the multivariable nature of HVAC systems which service large multi-roomed

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facilities (e.g. large office buildings). Factors such as whether the different zones in the building are internal, whether they have large or small windows, the extent of external walling, and the type of activities carried out in them, decide upon the needs of these zones in terms air- conditioning. The VAV scheme aims at catering for the air-conditioning needs in individual zones. The VAV technique was a step forward in that it decouples the large system and breaks into smaller (more) manageable units. Despite this, the resulting smaller units are still very much multivariable in nature, and it is the belief here that improvements in terms of dynamic performances and energy consumptions can be realised by using such models in a proactive way to sustain comfort conditions at a minimal cost.

Building systems can be also modelled by using first principle relationships (based on thermo-physical reasoning) which describe the thermal/mechanical nature of the system at hand. Usually, engineers shy away from this method unless absolutely necessary because specialist knowledge and a thorough understanding of the underlying physical process is required. It is also costly in terms of development time and only justified if the alternative is too risky. In some cases the models are simply too difficult to build and require vast computing resources.

In the approach adopted here, a model is obtained using identification techniques which allow the derivation of a model from actual data collected from the system. The models obtained in this case are empirical in that the parameters identified do not necessarily represent physical quantities or characteristics of the system. They are also normally linear and therefore dependent upon the operating point about which they were derived; nonlinear models can also be derived when appropriate. Typical identification techniques include least-squares and soft computing based methods.

Least-squares based methods allow for the inclusion of stochastic influences in a relatively straightforward manner. Such effects can represent the random disturbances on buildings (such as occupancy effects,...) as well as actual noise acting on the system, or can simply allow the user to represent numerically their lack of knowledge about the overall system; the model obtained can be designed to be and to 'work' even under conditions not considered in its derivation.

The models derived using these stochastic least squares based methods can be written such that they predict the changes in systems output over varying time horizons, thus allowing the controller to take action to counteract future disturbances in some optimum way. This is based on a proactive philosophy, by opposition to the prevailing trends where control actions are taken on the basis of currently-sensed output values rather than their predicted values.

Testing facility

The test facility used for the research presented here is located at the University of Bradford. It comprises three rooms. Two of the rooms have windows with secondary glazing; the third one is an internal zone. The rooms have false ceilings which cover a void housing the dedicated air handling units. The air conditioning system which serves the three rooms is of the VAV type, with terminal re-heaters. The activities in the three rooms are consistent with those found in standard office buildings, namely that the occupants can move freely around, they use electrical equipment, such as personal computers, printers and lighting of varying intensity.

Fresh air is drawn into a chamber, where it is mixed in selected proportions with air returning from the three rooms, controlled by a return damper. The resulting mixture, then enters the air handling unit which consists of a main heater, a filter, a cooler/dehumidifier and a humidifier. These units are used as required to control the temperature and moisture content of the air supplied to the VAV boxes which supply each room. A supply fan injects the pre-conditioned air into the distribution ducting and is controlled so as to maintain a constant static pressure. At the level of the VAV boxes, air flow and temperature can be controlled using a damper and the re-heater, respectively. Air is extracted from the rooms through square grilles using an extractor fan (see Figure 1).

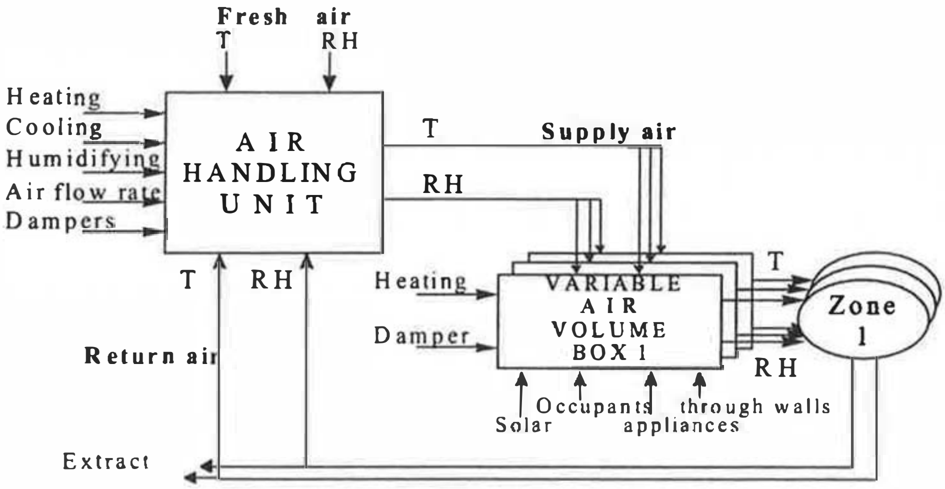


Figure 1 Diagram of BMS test facility

Control of the system is achieved by four networked commercial PLC type controllers. They are stand-alone units which can both report faults (by raising alarms) and communicate over the network using a serial protocol. The control strategies adopted are standard and felt not to make full use of the controllers/supervisor.

Note that, due the move of Professor Virk and Dr. Azzi, the research has been transferred to the University of Portsmouth where an improved full-scale BMS test facility has recently been commissioned and is the basis of current research into the model-based control of multivariable air conditioning applications.

Data acquisition

Data acquisition is normally carried out by the BMS supervisor trend plotting and/or archiving. As the data from the plant and room was required for modelling and real time processing, and since the particular commercial BMS used in this project allows Dynamic Data Exchange (DDE) with other Windows applications, it was decided that a software program would be developed to allow data monitoring and manipulation of system inputs. The protocol of communication with the BMS using DDE was released by the manufacturer and was used in our research.

Modelling methodology

The objective of the overall project is to build a mathematical model which will ba able to predict temperature and relative humidity in each of the three rooms. In order to do this, those variables having an influence on the system need to be identified so that proper instrumentation can be included for the sensing and data monitoring. From simple common sense reasoning it is clear that heating input rates (from main heater and reheaters), external temperature and relative humidity, cooling input rate, the humidification rate and the air flow rate will affect room temperatures and relative humidities. In addition, when considering one particular zone, temperatures and RHs from neighbouring zones, might need to be included in the model. Since the system use return air to minimise the use of heating resources during winter, the return air temperature and RH are also possible candidates for inclusion in the model. Therefore, models for, say zone temperature (Tz), can be represented as functions of these variables in the following manner:

$$T_z(t)+a_1T_z(t-T)+\ldots+a_{n_t}T_z(t-n_TT)=[b_{10}u_1(t-k_1)+b_{11}u_1(t-T-k_1)+\ldots+b_{1n_1}u_1(t-n_1T-k_1)]+\ldots+$$
$$[b_{m0}u_m(t-k_m)+b_{m1}u_m(t-T-k_m)+\ldots+b_{mn_m}u_m(t-n_mT-k_m)]+$$
$$[c_0e(t-k_e)+c_1e(t-T-k_e)+\ldots+cn_ee(t-n_eT-k_e)]$$

where the a_i's, b_{ij}'s and c_i's are the model parameters which need to be identified. k_i's and k_e are the dead times associated with the inputs to the model and e a white noise process representing stochastic disturbances acting on the system, which also need to be identified. T is the sampling interval.

In order to identify these parameters, tests which excite the system dynamics have to be designed and carried out and the resulting data is used to derive the models; the overall modelling procedure is shown in Figure 2.

Several issues need to be considered when designing trials so that the most appropriate data is generated and gathered for modelling purposes. These issues are discussed at length in Virk *et. al.* [1] and can be summarised as follows:

- Step tests have to be conducted to identify characteristic time constants in the system.
- The dead time, or transport lag (see, for example, D'Azzo and Houpis [2]) in the system, is the time taken for the system to respond to a stimulus and must be identified.
- The effect of drifts must be minimised
- Sampling rate must be chosen carefully so as to avoid over or under sampling. In the former case, high frequency noise components which might not be relevant to the system could be included in the data. In the second case, the data could lack information about the transient dynamic behaviour of the system.

The Pseudo Random Binary Signal (PRBS) (Briggs and Godfrey [3]) is one of the most popular test signals for exciting system dynamics and is the one used as part of this research. Characteristics of the PRBS (clocking period and word length) are discussed in Virk *et. al.* [1] for the interested reader.

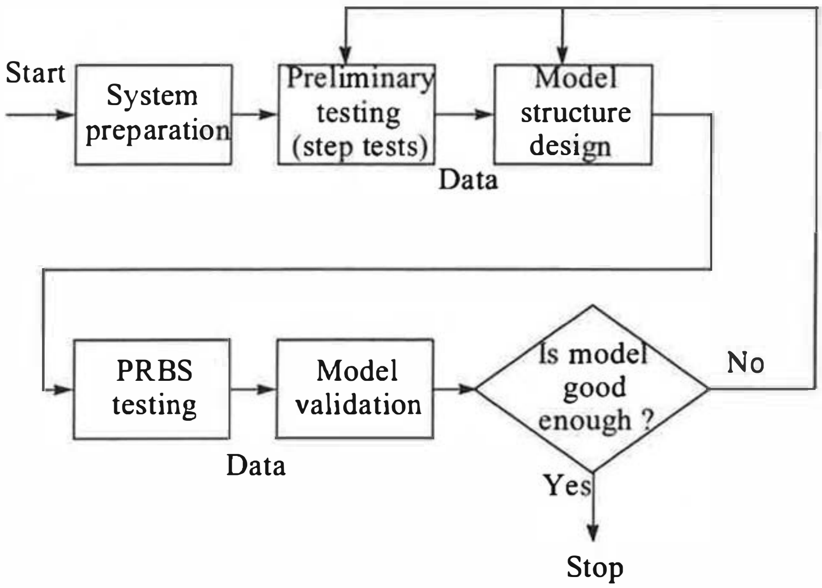


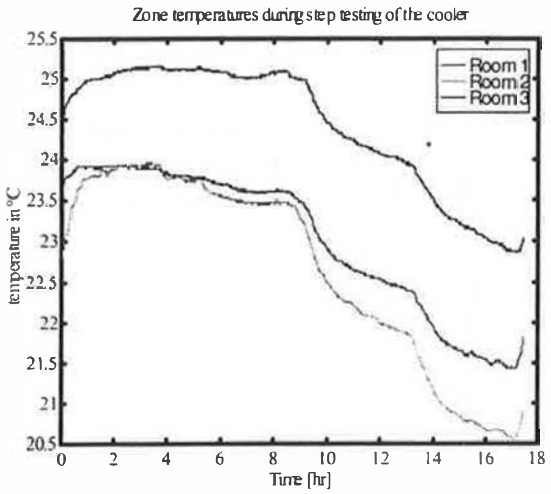
Figure 2 Block diagram of modelling procedure

Execution of trials

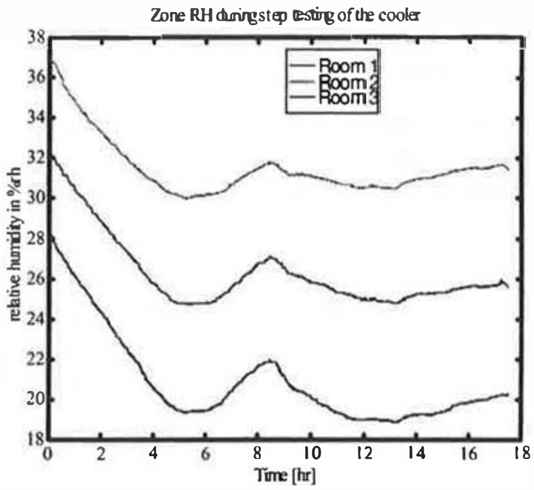
In terms of actuators, the system has five inputs at the level of the air handling unit (AHU) and two inputs per VAV box (see Figure 1). Two outputs per room are considered in this study: zone air temperature and zone relative humidity. In addition, the system is subject to several disturbances which include; climatic conditions, occupant-induced effects and those due to say furniture variations etc. In this case the variables monitored are the fresh air temperature and relative humidity. In addition to these stochastic disturbances, other variables are taken into account when modelling the system.

These are the temperature and relative humidity of the return air (inputs to the air handling unit) and the supply air temperature and relative humidity (inputs to the VAV box).

Step tests on the system were performed by applying perturbations of changing amplitudes to each input to the system. In order to avoid the problems of saturation and linearity, the step tests were carried out across the range of operation of each input. Four steps of equal amplitude (25%) were applied in succession at time intervals long enough for the system to settle to near equilibrium (2-6 hours, depending on the actuator tested). Figure 3 (a), (b) show a sample of the type of responses obtained from step testing the system. The curves are the responses of temperature and relative humidity to step tests on the cooler. As can be seen, the responses are not always perfect steps due to the disturbances acting on the system as well as its inherent nonlinearities. The external air temperature is one of these disturbances and is shown in the case of each experiment. Repeatability (*i.e.* achieving the same output for the application of the same input) is normally a problem in such systems, and is so in this case because the system is subject to several other significant influences (*i.e.* the disturbances); the result is that for identical control inputs, different output responses will be obtained.



(a)



(b)

Figure 3 Step testing of cooler

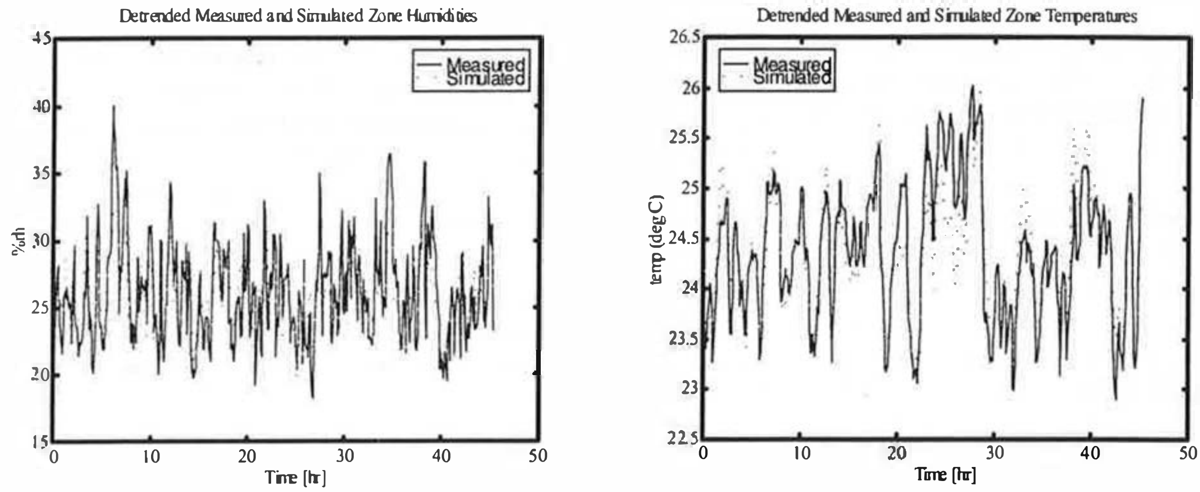
This is not of critical importance as the step testing are merely aimed at providing an indication of the order of magnitude of the time delays and predominant time constants involved in the system. The majority of the time delays observed in the system are in the range 1 to 8 minutes, and on the basis of this distribution it was decided that the sampling interval for testing purposes should be 1 minute; re-sampling is then possible in order to achieve lower sampling rates, if necessary. In a similar way the dominant time constants in the system were identified by examining the step responses of temperature and relative humidity.

Having established some preliminary knowledge about the system, it is necessary to determine the structure of the model and the parameters which best describe the dynamic behaviour of the system. To do this optimally requires suitable excitation signals to drive the various inputs, such that all the important modes are perturbed and contribute to the output response. In this way, the data collected contains information on all the relevant modes of the system. For example, if the excitation signals excite only parts of the dynamics, then only these excited portions will contribute to the output, and hence 'appear' in the resultant model. the portions not excited will remain 'hidden' from the identification procedure; this could lead to problems in operation caused by use of an unrepresentative model in circumstances where these hidden modes are active.

Modelling exercise and validation

In the modelling phase the data obtained through the PRBS tests is used to compute the parameters of a regression type model for one room in the testing facility. The PRBS test signals were generated using a method based on digital logic and shifting registers (Virk *et. al.* [1]). The model is a lumped parameter one, *i.e.* the outputs (temperature and RH), are represented by one output variable each. Although the PRBS tests were conducted on all three rooms simultaneously, in the following discussion, we will be looking at one room only out of the three available. The procedure outlined here is repeated for the two other rooms.

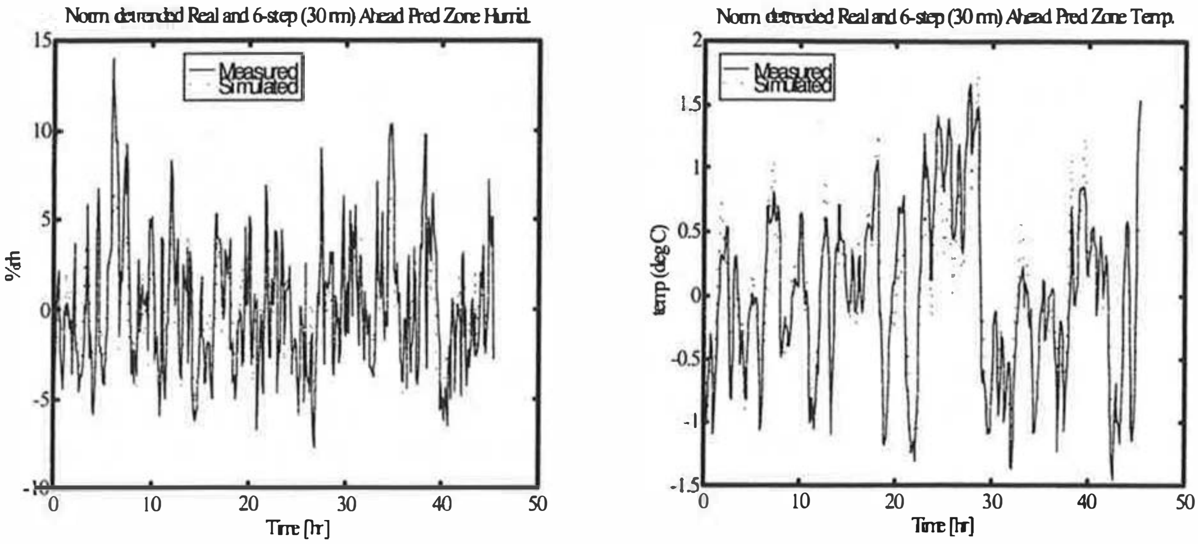
The model chosen in this case has an ARMAX (Auto Regressive Moving Average with eXogenous inputs) structure (similar to that shown in equations 1 and 2), the order associated with any input is not higher than 3. In the case of the temperature, the input variables used in the modelling are: the fresh air temperature, air handling unit supply air temperature, inputs. The model for zone humidity has the following input variables: the zone air temperature, AHU air supply temperature and humidity, the inputs from the main heater, the cooler, the humidifier, the supply fan, the VAV damper and the VAV reheater. All of the inputs to the system were driven by uncorrelated PRBS signals during testing.



(a) **(b)**

Figure 4 Batch validation of model derived

Figure 4 shows the model output compared with the real data (temperature and relative humidity). The behaviour of the system is simulated over a period of 48 hours. The performance of the model in predicting temperature and relative humidity is good. The model developed was used to predict temperature and relative humidity over a horizon of 30 minutes, that is 6 step-ahead. The performance of the model is shown in Figure 5 (a) and (b).



(a) (b)

Figure 5 6 step-ahead (30 minutes) prediction performance from model

As can be seen the predictions from the model are very good. The correlation analysis remains to be carried out and will be part of future work. In the case of the temperature the error predictions are, for all models, well contained between +1 and -1°C. This is an encouraging result in terms of control of temperature conditions. It means that the predictions to be used in the calculating the corrective actions for predicted perturbations will be reliable. In the case of relative humidity the error predictions are on the whole within ±8%rh. Although this figure seems large, combined with the standard deviation values of the residuals sequence (Table 1) in each case, we can see that the performance of the model is good. In addition in terms of comfort the requirement for relative humidity control is not as not as stringent as in the case of temperature. Generally relative humidity can take values anywhere between 45 and 55%rh without loss of comfort; where as temperature has to be maintained to within ± 2°C of the set point.

Note that this is the result of one series of PRBS tests carried out on the Bradford testing facility and that there was no opportunity to iterate the modellling process to refine the results obtained.

Table 1 Comparison of model performance in the case of batch, 1, 6 and 100 steps-ahead predictions

Comparison of Residuals	Temperature		Relative Humidity	
	Mean	Standard Deviation	Mean	Standard Deviation
1 step-ahead	0.0066	0.069	0.0062	1.6693
6 steps-ahead	0.0062	0.2579	0.0066	2.0914
100 steps-ahead	0.0066	0.313	0.0079	2.1152
Batch	0.0069	0.3157	-0.0103	2.1279

Conclusions and future work

Preliminary results from an exercise aimed at developing regression models for the operation of BMS systems, have been presented. The variations of space air temperature and relative humidity in one office within the Bradford test facility have been successfully modelled and predictive models for 5, 30 and 500 minutes ahead prediction horizon have been derived. The results obtained here are promising in terms of the usage of these models to control and operate BMS installations. The quality of the predictions is such that the effect of disturbances (which cause delayed responses in the system) can be significantly reduced, thus yielding smooth operation of the system. In addition, the models can also be used to detect faults in the system; for instance the regular monitoring of a parameter such a the standard deviation of the residuals (error between predictions and actual data) over a moving data window of fixed length, could be an indicator of the health of the system. The method of system control/status monitoring proposed here, presents clear advantages over current trends where control decisions are based on current (and past) system variable values rather than their forecast variations. Current work on the University of Portsmouth test facility, is extending these batch models to multi-zone situations and then to on-line (self-adaptive) formats. Once these models have been validated their potential in control and fault detection will be investigated.

It is the intention of the BMS research group at the University of Portsmouth to extend the model-based approach to optimize the operation of low energy buildings; these buildings include those which use (partially or totally) natural ventilation strategies. The newly commissioned Portland Building (which houses the School of Architecture) is being used as an in situ test bed to assess the potential of the advanced methods. A monitoring exercise is being carried out to assess the procedure for designing low energy buildings. This study is being carried out in conjunction with the BRE, Hampshire County Council and an industrial partner (window manufacturer). Similarly, the idea here is to develop predictive models to assist in the efficient ventilation of the building throughout the year.

In addition, the BMS research group has teamed up with a company on the Isle of Wight which has developed a prototype energy harvesting system based on the endothermic effect where ambient energy is absorbed and used as required. The prototype system comprises an integrated roof product made of extruded aluminum and through which a water/glycol mixture is pumped. The energy collected by the roof is transferred to heat stores where it is upgraded (via heat pump technologies using low tariff electricity) and then used to provide heating and hot water as required in a number of applications. Some possible areas where endothermic systems are being considered include the domestic sector, horticulture and sewage treatment. The BMS research group is currently monitoring the prototype on a regular basis and the data collected will be used to develop a model-based solution which allows efficient overall operation of the overall endothermic system.

References

1. Virk, GS, Cheung, JYM and Loveday DL, Practical stochastic multivariable identification for buildings, The journal of applied mathematical modelling, Vol 19, no 10, pp 621-636, 1995.
2. D'Azzo, JJ and Houpis, CH, Linear control system analysis and design: Conventional and modern, Second Edition, McGraw Hill, Tokyo, 1981.
3. Briggs, PAN and Godfrey, KR, Pseudo-random signals for the dynamic analysis of multivariable systems, Proceedings of the IEE, Vol 113. no7, pp.1257-1267, July 1966.

Measurement of moisture migration in building materials

H Saidani-Scott and B. Day, University of Bristol[1]

Summary

There is an urgent need for improved theoretical models for moisture flow in building materials and guidance for the design against a wider range of problems, in particular those associated with transient and mixed phase situations. These new theoretical models require more detailed physical parameters to be determined for most building materials. This paper describes an experimental apparatus and methods of use developed at Bristol for providing these data.

The need for improved models

Sustainable cities need durable buildings ; one of the chief causes of unanticipated failure of building fabric is the penetration of water, either as vapour (with condensation) or by capillary attraction in porous solids. Many architects and builders would probably say, if asked, that the flow of water in building materials is understood and predictable. Certainly, texts such as Seifert's "Damp, Diffusion and Buildings" and the numerous BRE publications provide plenty of detailed design advice derived from scientific analysis. However although there may be truth in the complaint that :*"There is no problem, however complicated it may be, that an academic cannot complicate further",* the need for complication is in this case justified. There is increasing evidence that the simplified models that generate this advice do not take account of phenomena that can have important consequences for the properties of a piece of building construction. The most widely adopted technique (for prediction of interstitial condensation (Appendix: Plate 1)) depends on assumptions of steady boundary conditions and linear physics, based on the idea that water vapour passes through a porous solid as a vapour, without reacting with the walls. Given this, and other assumptions, behaviour is quantified in terms of the "vapour resistivity" (or reciprocal, "vapour permeance") of the material of each layer, and vapour pressure and temperature regime. "Vapour resistivity" can be determined by a standard "wet cup method" although each test takes several weeks to complete.

Unfortunately, although this simple model often leads to "safe" advice, it is far from an accurate representation of reality. Water molecules interact strongly with pore walls of most building solids, so that moisture is unlikely to pass like a gas down the centre of hollow pores as the "vapour resistance" concept would have it, except at very low humidities. A more realistic view of the physics, involving multiple phase regimes, is set out in appendix Plate 2. It is hardly surprising that in these circumstances the movement of water in porous solids can no longer be expected to be a linear diffusion process characterised by a single parameter, the vapour resistivity. For the design problem for which the simple model was devised (long term, steady state), the more sophisticated view does not often alter the advice. But for study and design for other problems, such as :

- design for transient conditions (e.g. surges of vapour load)
- estimation of risk under variability between samples of a given component
- prediction in situations of simultaneous liquid and vapour diffusion (e.g. drying out of wet walls)
- prediction of rate of condensation (vapour flow, effects of latent heat)
- design for liquid transfer from sites of condensation (remote corrosion effects)
- prediction of effects of moisture content on effectiveness of thermal insulation
- study of the application of hygroscopicity of building materials for humidity control
- allowance in thermal design for contribution of latent heat to thermal storage effects

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progress will require the introduction into the model of the parameters of table 1 :

PROPERTY	DEFINITION	EQUATION
vapour diffusivity [1]	D in the diffusion equation based on concentration C,	$\frac{\partial C}{\partial t} = D\frac{\partial C}{\partial x}$
vapour resistivity	R in Ficks Law :	$\frac{\partial C}{\partial t} = R\frac{\partial p}{\partial x}$
vapour capacity	c in the vapour pressure based diffusion equation	$\frac{\partial p}{\partial t} = \frac{1}{Rc} \times \frac{\partial^2 p}{\partial x^2}$
Liquid diffusivity, resistivity and capacity	analogous to 1,2,and 3 above	
Thermal diffusivity, resistivity and capacity	analogous to 1,2,and 3 above	
Sorption-desorption curve	variation of C with ambient humidity	links C with p

Table 1 - Parameters for advanced moisture movement models

Computer models to aid design, incorporating these concepts and quantities, are under development and trial application in a number of centres world wide. Although some existing data have been collected [**2**], there is an urgent need for measured values of these more sophisticated parameters for building materials, coupled with a requirement for more rapid methods of measurement for those quantities requiring a statistical description. That is the purpose of the apparatus described here.

Description of experimental apparatus and procedures

The core of the experimental apparatus is a system for providing a controlled , variable humidity space, the "sample box" (figure 1.). This is used in two main ways:

- As a variable environment within which mass change experiments are conducted (sorption-desorption and a variation of wet-cup/ dry-cup methods)
- The "sending" space for transmission tests: the flow of moisture through a sample is measured when the sample is used as a separating membrane at the top of the sample chamber.

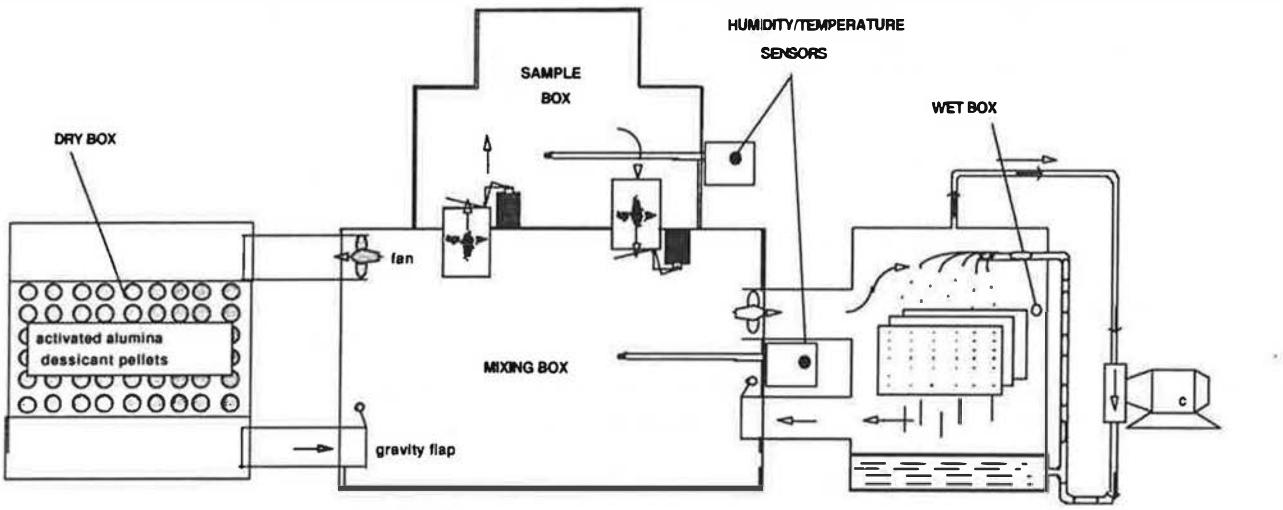


Figure 1: Diagram of the experimental apparatus.

The volume of the largest of these boxes (the mixing box) is about 300 litres. The humidity conditions in the sample chamber are under computer control and constantly adjusted to the required or pre-programmed variation of relative humidity (RH%) or vapour pressure. This is achieved by controlling a mixture of calculated amounts of saturated or dry air in a buffer "mixing box" to achieve a humidity, that when mixed with the air in the sample box will result in the required conditions. This two stage process gives the opportunity of varying the "strength" of the error correcting signal (that is the difference between mixing box and sample box humidity), depending on how far the controlled variable is from the target value. This gives maximum speed of response for large error or rapid change, with control finesse when only small adjustments are required (See Figure 2 and Figure 3).

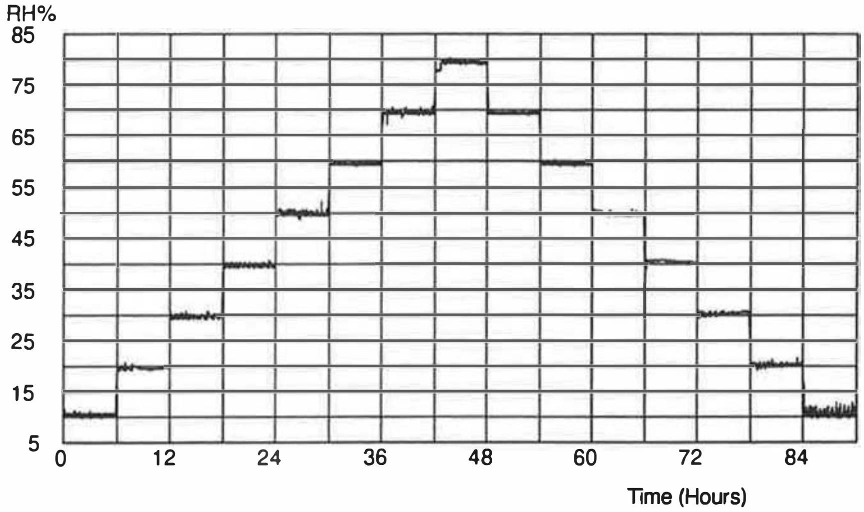


Figure 2: Sample humidity control for steps up and down.

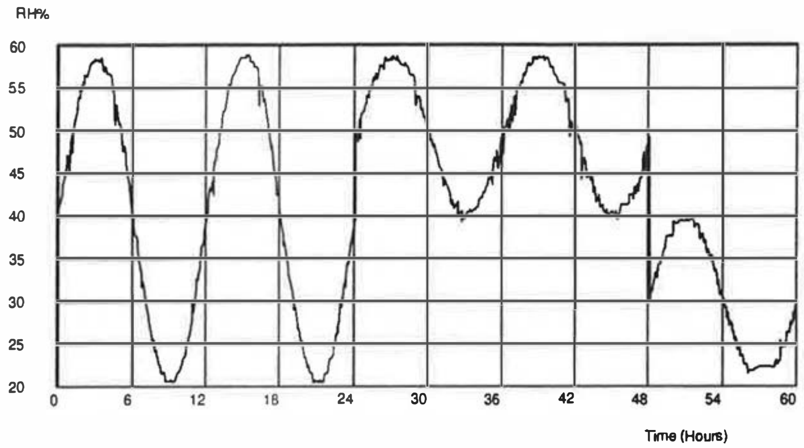


Figure 3: Sample humidity control for multiple sine functions

There are three modes in which the apparatus can be used :

Mode 1: Sorption-desorption experiments

In this mode, a sample of the material under test is suspended in the sample chamber from the underside of a digital balance and weight variations monitored as humidity is altered. Samples may be as small as 1 or 2 cm^3.

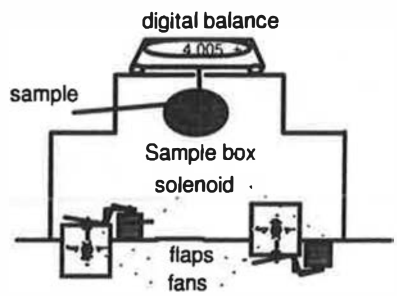


Figure 4: Sorption-desorption arrangement

A series of steady state RH% values are imposed (rising or falling steps) ; the sample is held at each rh% until it reaches equilibrium moisture content.

It can be seen (Figure 5) that a 3.3 mm thick sample takes approximately 15 hours to reach a new equilibrium (sample initially dry.)

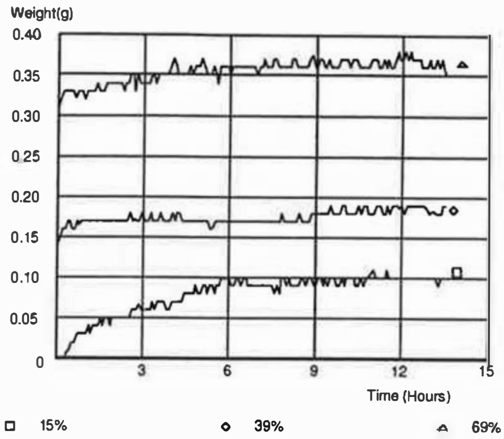


Figure 5: Equilibrium state under various RH%

The resulting sorption-desorption curve (moisture content v. humidity) may be traced out in a period of about 4 or 5 days. However if the geometry is simplified (e.g. by forming the sample as a cube with five sides sealed, thus achieving one dimensional diffusion) the rate at which the equilibriium moisture content is approached can be used to yield diffusivity values directly [3].

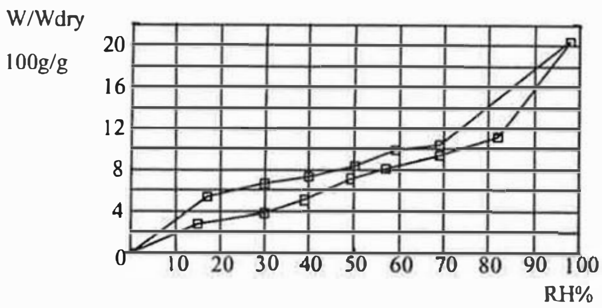


Figure 6: Sorption-desorption curve for a pine sample

Mode 2: Dry-cup and wet-cup experiments

In the present standard method to determine permeance, one observes the long term rate of loss or gain of water passing through the sample forming the lid of a "cup" located in a dry or humid atmosphere, and containing water or dessicant. The use of thin sample layers and micro - balances with digital logging gives substantial reduction in experiment time over the standard method. The vapour flow rate is equal to the rate of mass loss or gain, while the vapour pressure is simply the difference between the values inside and outside the cup. The vapour permeability is thereby found but the use of mass gradient (v. time) and gives better accuracy than traditional techniques. It is also possible to use intermediate values of sample box humidity or standard solutions inside the cup in order to determine vapour permeability at varying moisture content, making it possible to investigate non-Fickian diffusion.

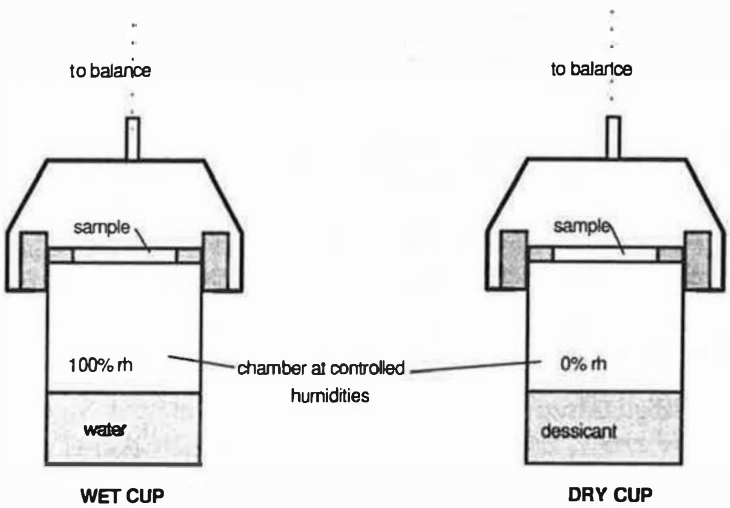


Figure 7: Dry cup/ wet cup arrangement

Mode 3: Permeation experiments

This uses the principle of measuring the rate of effusion of moisture into very dry air, by its effects on the moisture content of the air stream after it has passed over the effusing surface. Electrolytic hygrometers [4], capable of absolute measurement of moisture content, down to a few ppm (part per million per volume) of moisture content in the air stream are used. This corresponds to moisture flow rates of the order of micrograms /seconds. Since the flow rate of the dry air could be reduced below present values (5l/mn), the potential is available for even lower flow rate measurements. The transit time for the dry air passing across the top surface is around 5s, so that rapid changes in effusion rate can be observed accurately.

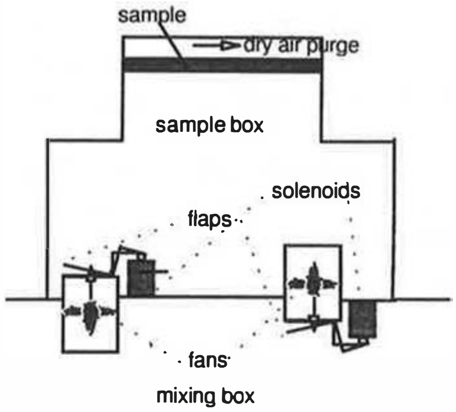


Figure 8 Permeation arrangement

Conclusions

The apparatus described , has facilitated a number of techniques for determining a variety of moisture parameters. The general principle embodied in the apparatus is to use transient observations rather than rely on steady- state results only, as has been the case with traditional methods. This has made it possible to obtain results more quickly than hitherto, thus enabling it the collection of statistically significant sample numbers for variable materials **[5, 6, 7, 8**].

References

1- **J. CRANK**. The mathematics of diffusion. Second edition. Clarendon Press. 1975.

2- **INTERNATIONAL ENERGY AGENCY.** Catalogue of materials properties. Energy Conservation in Buildings and Community Systems Programme. Report Annex XIV, Vol 3. pp 2.16. 1991

3- **H. SAIDANI-SCOTT.** Analysis of moisture migration in porous media: application to building materials. PhD thesis. Bristol University. U.K 1993.

4- **SALFORD ELECTRICAL INSTRUMENTS LTD**. S.E.I. electrolytic hygrometer. Mark III and Mark IV.

5- **B DAY and H SAIDANI-SCOTT**. Investigations of moisture transfer into drums of tobacco leaves. Report for HANSON PLC. 1993.

6- **H. SAIDANI-SCOTT, B. DAY and K. G. EVANS.** Measurements of the vapour characteristics of white pine. Contribution to the IEA Meeting. Glasgow. May 1993.

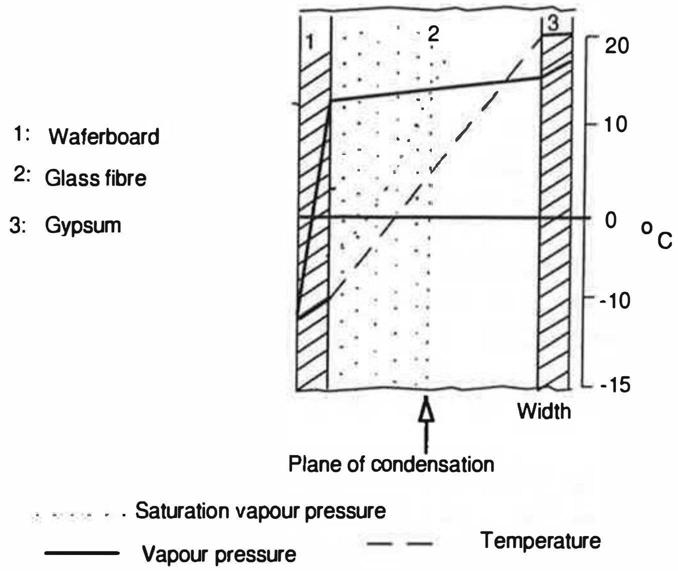
7- **H. SAIDANI, B. DAY and K.G. EVANS**. Computerised apparatus for the experimental study of heat and mass transfer in porous bodies. 2nd MINSK International heat and mass transfer forum. BELORUS. 1992.

8- **B DAY and H SAIDANI-SCOTT** A study of corrosion of galvanised steel beneath PVC paint films. report for case and Sons Ltd. 1992.

9- **M. BOMBERG**. Moisture flow through porous building materials. Report 52. Division of Building Technology. Lund Institute of Technology. 1974.

Appendix

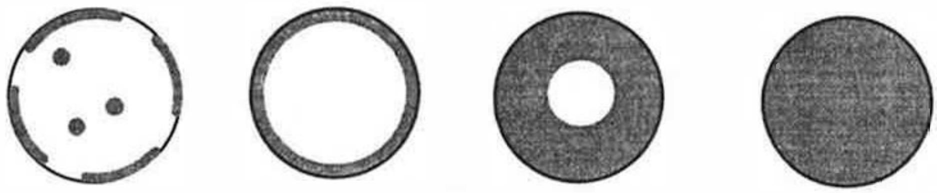
Plate 1: Simple linear model for interstitial condensation (glaser model)



The model is based on the assumption that the main source of moisture in building fabric is excess water vapour present inside a building because of occupant activities. The consequent vapour pressure surplus drives vapour through the porous fabric (assumed inert), down a pressure gradient determined by an analog of Ohm's law. At the same time the heat flow caused by in-out temperature difference sets up a temperature gradient, also assumed linear (Ohmic) in any single layer. There is a maximum ("saturated") value of vapor pressure associated with any temperature ; since the free air (inside and outside) cannot be more than saturated, any single material layer will also remain below saturation throughout its thickness. However if a composite construction presents (from inside to outside) low vapour resistance layer / high vapour resistance layer with high thermal resistance / low thermal resistance the interface will be subject to condensation as the arriving vapour is cooled below its dew point.

Plate 2: Models for diffusion behaviour in porous solids

This contemplates the following progression : at very low humidity, isolated water molecules are attached to, but able to move across, the surfaces of the pores. As humidity is increased the number of attached molecules increases, forming first rafts of water molecules which then grow until a continuous mono-molecular layer is formed ; diffusion in this layer may be much faster than through pore-space. At still higher humidities more & more water molecules become attached, building up to a liquid lining, that eventually fills the narrower pores, so that flow may now be driven by capillary forces [**9**].



1) Knudsen 2) Monolayer 3) Liquid lining 4) Fully flooded

An experimental and theoretical study of the stability of stratified hot smoke in tunnel fires

M.Tabarra, B. Kenrick & R. D. Matthews, South Bank University[1]

Summary

The results are presented of a programme of research in the UK under the ROPA scheme, funded by the EPSRC to study the characteristics of a hot stratified smoke layer in a 1/15 scale model tunnel under conditions of natural convection. The project made use of experimental data to benchmark computational fluid dynamic output. Once the validity of the CFD model has been established, attention can be turned to modelling the movement of fire smoke in full-size tunnels, which needs a larger number of grid elements for a comparable level of resolution. This coupled with an investigation of aerodynamic interactions between ventilation flows and a hot stratified smoke layer could be used in arriving at a correct smoke management strategy for fires in vehicle tunnels and other underground spaces.

CFD velocity and temperature field results of the buoyancy-driven smoke flow due to a fire at the end of a closed horizontal model tunnel (cavity) have been compared with the experimental data. The results show excellent qualitative agreement (hot and cold streamlines) and good quantitative correlation, after taking into account the effect of radiation losses. The results can be progressively improved if more of the physics of the flow is modelled either by including first radiation, then more appropriate turbulence modelling and finally combustion models, but these need far larger memory capacity and computational run times.

The effect of blockages in the hot smoke stream were also shown to be dependant on the size of the barrier, as well as the distance from the fire correlating with Ri number. Further investigations are needed to quantify these preliminary findings in terms of barrier geometry, position and distance from fire, the tunnel geometry, the local velocities and Ri number.

Introduction

This project arose from the widespread knowledge that the most immediate threat to life in tunnel fires comes not from a direct exposure to fire heat but from the effects of smoke inhalation. More recently, it has come to light that strong forced ventilation flows may not be the best answer to passenger safety, as this tends to mix the hot smoke layers with the cool fresh air drawn in by the fire. While city centres throughout the world are looking to Metro systems for mass transit, the horrors of King's Cross London in 1987 and Baku in 1995 make optimum ventilation and smoke movement systems mandatory.

The work done between 1991-1995 on the longitudinal ventilation of tunnels by jet fans [1] funded by the EPSRC/DTI and industry, stimulated the authors' interest in the critical interaction between the smoke from a fire in a tunnel and any ventilation flows or obstructions present in the tunnel. This ROPA project was aimed at establishing an experimental model of stratified smoke behaviour and using this to benchmark a computational fluid dynamic (CFD) model. The project has so far been a blend of experimental and theoretical study in which the steady-state temperature and velocity profiles in the hot tunnel model have been compared with the CFD data. Primary and secondary modes of destratification have been identified. *Primary* destratification occurs near obstructions in which strong transverse or streamwise vortices bring smoke down into the cool clean air, where it cools and mixes.

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Secondary destratification occurs gradually and continuously along the tunnel as the cooling smoke boundary layer creeps down the tunnel walls and into the air below the stratified layer. It seems that the point at which primary destratification can be triggered depends mainly on the ratio of buoyancy forces to inertia forces or the Richardson number, Ri.

While recent research has concentrated on accurate modelling of combustion and the realistic prediction of turbulent flames, the ROPA project has focussed on far-field modelling of smoke layers and their stability under real tunnel conditions. An early paper by Heselden [2] provided the impetus for smoke movement studies and has influenced the succeeding studies. Based on full-scale fire tests, Heselden raised many illuminating questions and proposed future research fronts, many of which can only now be attempted with the advancement in CFD capabilities. The crucial role of turbulence modelling and the effect of stratification on turbulence damping was recognised early on [3], and CFD field modelling of fire smoke was underway by the mid 1980's. These studies were limited by the then current computer power and memory and were often conducted on coarse grids without radiation modelling leading to large errors. The absence of a detailed experimental data base to benchmark CFD results also added to the uncertainty of computational results. In the last three years, many researchers are using the increasing computational capacity to good effect and modelling fires in complex structures, accounting for combustion chemistry and radiation in 3D geometry [4,5]. The interest is world-wide and will be complemented by a set of comprehensive data from full-scale fire tests in the Memorial Tunnel in the U.S.A. which will be an invaluable reference for benchmarking full-scale CFD results for years to come.

The ultimate beneficiaries of this work will be the travelling public, who in the event of a fire in a tunnel will receive rapid and unambiguous instructions to make good their escape. This will be due to an integrated telematic communication and ventilation control system aware of the position and power of the fire and the stability of the stratified smoke along any escape route. The commercial beneficiary of the research will be the consulting engineer, fan and ventilation system provider who will have a deeper understanding of smoke behaviour and hence a competitive edge when bidding world-wide for tunnel ventilation schemes.

Project aims and objectives

The aim of the project was to model the behaviour of hot stratified smoke in tunnels. The CFD model would be verified in stages of increasing complexity using experimental temperature and velocity data from the 1/15 scale model tunnel. In particular the research would seek to enhance our understanding of the stability of hot stratified smoke and begin to formulate strategies where this behaviour could be put to good use in tunnel ventilation design.

To achieve the aims and objectives, an extensive experimental program was undertaken using 2 different tunnel lengths, where temperature and velocity data were gathered. In parallel, intensive CFD studies were performed and the model continuously enhanced to match the experimental data more closely.

Experimental study

The experimental scale model tunnel consisted of a rectangular section 300 mm wide and 500 mm high containing a variable, controlled gas fire source. The tunnel length is variable up to a maximum of 14 m, thus representing a full-scale single-lane tunnel 4.5 m wide, 7.5 m high and up to 210 m long, as shown in Figure 1. In order to avoid the undesirable effects of slight portal pressure fluctuations which could cause uncontrollable time-variant natural draughts along the tunnel, it was decided to close one end. The end wall can be effectively viewed as a plane of symmetry for an induced natural ventilation flow in a horizontal tunnel, simulating a fire in the middle of a tunnel twice the length, offering significant savings in computational time and memory space as well as experimental time. The roof was insulated with rock wool, and the side walls were made of glass to allow the laser Doppler anemometer (LDA) beams through for velocity measurements anywhere in the tunnel. The LDA system used was a Dantec two component type based on a 300 mW Argon laser capable of giving both mean and turbulence velocity data in the axial and vertical directions. The temperatures were measured by a K-type thermocouple tree, which could be erected at predetermined (1 m interval) locations along the tunnel at mid-plane and at 20 mm off one of the glass walls. Preliminary temperature measurements verified the temperature field to be effectively two-dimensional, hence no provisions were made for further measurements across the tunnel width. A maximum fire power of 4.9 kW (representing a full-scale equivalent of ~ 4 MW) could be established via two conventional ceramic gas hobs, installed side by side to occupy a floor area of 200 x 300 mm wall to wall, which would take about an hour for the tunnel temperatures and the cold feed and hot return flow to reach steady state.

The experimental programme comprised of three sets of tests; a 3 kW fire in a 5 m long cavity, a 4.9 kW and a 3 kW fire in a 9 m long cavity. In each set, the velocity field was recorded after thermal stability was reached whereas the temperature field was recorded during the initial transient phase of warming up as well as the subsequent stable phase.

For the 5 m cavity, velocity and temperature values were recorded at 0.7 m, 1.7 m, 2.7 m, 3.7 m and 4.7 m from the end wall, whereas for the 9 m long cavity, only temperature data was recorded at 3.7 m and 4.7 m. At each of the above cross-sectional planes, the temperature was recorded at 8 non-uniform (clustered at the top) vertical positions both at the mid plane and at 20 mm of the back glass wall, whereas the velocity was recorded in a uniform grid of 20 mm squares across the plane, resulting in 336 measuring points at each YZ plane.

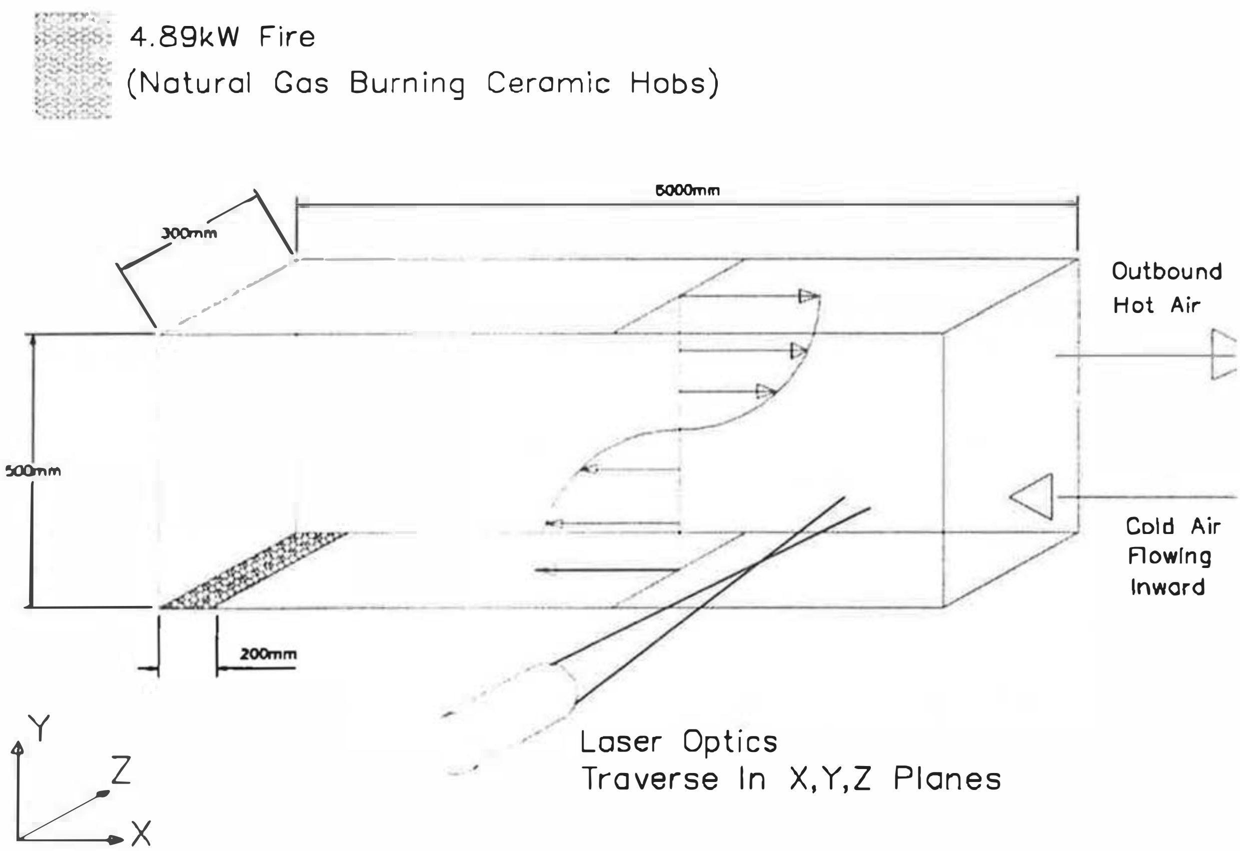

Figure 1: Experimental test rig

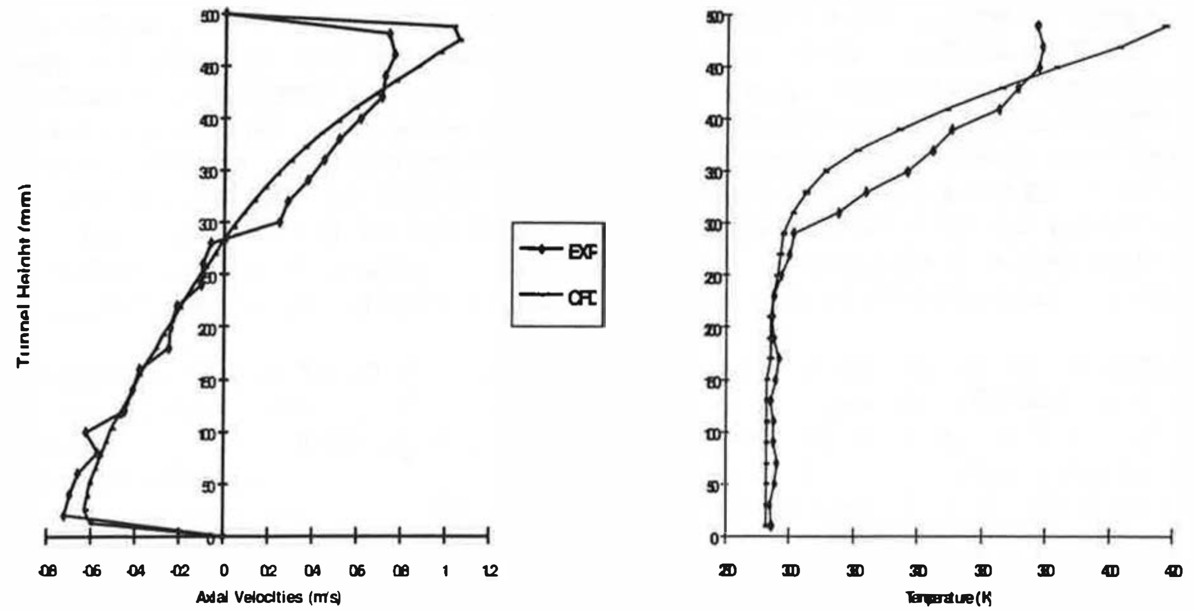

Figure 2 **Comparison of CFD results with experiment: velocity and temperature profiles for a 4.9 kW fire**

CFD study

The computational fluid dynamic facilities consisted of a DEC Alpha 3000/400 computer with a processor speed of 133 MHz and 48 Mb RAM (later increased to 96 Mb), running the CFDS-FLOW3D (later updated to CFX 4) software package developed by AEA Technology, which is a finite-volume general purpose code with a range of features for the study of heat transfer, radiation, two-phase flow, combustion etc.

The tunnel was modelled using the SIMPLEC algorithm with various differencing schemes. The modelling initially started with the simplest approach employing a 2D adiabatic field with the fire modelled as a heat source, a standard k-ε model and no radiation effects, pertaining to stage 1 in Table 1 which shows the possible modelling approaches in the order of increasing complexity. In this phase of the project, CFD simulations from stage 1 to stage 3 were planned, in order to study the effect of each improvement in the modelling approach. CFD fire combustion models, transient studies and Reynolds Stress models are known to be not only computationally intensive, but also of dubious merit to warrant attention at this stage and were thus left out of this phase of validation.

Table 1. CFD modelling of fire smoke in tunnels - stages of increasing complexity

Stage	Modelling Approach					
1	Steady 2D,	buoyancy driven,	adiabatic,	fire as heat source,	standard k-ε model,	no radiation
2	,,	,,	heat loss through roof,	,,	,,	,,
3	Steady 3D,	,,	all heat losses,	,,	,,	,,
4	,,	,,	,,	,,	corrected k-ε model,	,,
5	,,	,,	,,	,,	,,	with radiation
6	,,	,,	,,	fire combustion model,	,,	,,
7	Transient 3D,	,,	,,	,,	,,	,,
8	,,	,,	,,	,,	Reynolds Stress model,	,,

For a stage 3 approach, using a 50,000 node grid, more than 45 Mb of RAM space and about 6000 iterations taking 2E+05 seconds of processor time were needed. The results of a stage 3 simulation are compared with experiment in Figure 2. As expected, the CFD results follow the general trend well, but overshoot in velocity and temperature in the hot stratified smoke layer. This is because the heat losses through radiation have not been modelled, giving excessive energy to the smoke layer in the CFD model. Also the sharper temperature and velocity gradients observed in the experiments have not been properly captured in the CFD, because the k-ε model used was not corrected for turbulence suppression due to density gradients. Further stages of CFD modelling are certain to improve the accuracy of the simulation results, albeit increasing computational costs and memory requirements.

It is expected that accuracy will improve to within 10% by stage 6, where all the physical complexities have been modelled in one way or another. Stages 7 & 8 will also take into account the transient development of smoke flow in the time span between fire start and the establishment of a stable stratified smoke layer. In order to appreciate the complexities involved, Bettis recently reported a stage 7 simulation, which took 60 hours of CPU time on a Cray XMP super-computer [6].

Since the final thrust of the project is the interaction of hot stratified flow with barriers (like traffic signs and panels) and the stability of stratification, the effect of blockage in the hot smoke flow was studied in a preliminary investigation for a 35 m long tunnel where a thin panel spanning the whole tunnel width was installed at 30 m from the fire (5m from the portal). Two panel heights of 1/4 and 1/2 tunnel height were investigated. The 1/4 height panel appeared not to affect the stability of the hot layers greatly, whereas the 1/2 height panel caused enough disturbance for recirculation of hot smoke into the lower cold stream to cause mixing (Figs 3 and 4). This result showed the importance of blockage size in the flow and its effect on the stratified flow. Further studies will be needed to quantify these effects fully.

Full-scale CFD modelling

It is realised that full-scale CFD modelling of smoke in large structures and facilities will need grid elements and hence CPU time and memory several times larger than those mentioned above. Once the CFD model is validated against the small-scale experimental model, one can then apply it to a full-scale geometry with greater confidence. The scarce availablity of reliable full-scale test data from tunnel fires makes this approach a necessity, further justifying the approach adopted in this project. The validity of small-scale testing in fire smoke investigations has been further verified with the work of Oka & Atkinson [8] carried out at the Health & Safety Laboratories in the UK on a 1/10 scale model tunnel.

Conclusions

CFD velocity and temperature field results of the buoyancy-driven smoke flow due to a fire at the end of a closed horizontal model tunnel (cavity) have been compared with the experimental data. The results show excellent qualitative agreement (hot and cold streamlines) and good quantitative correlation, after taking into account the effect of radiation losses. The results can be greatly improved if more of the physics of the flow is modelled either by including radiation, more appropriate turbulence or combustion models, but these need larger memory capacity and computational run times.

The effect of blockages in the hot smoke stream were shown to be dependant on the size of the barrier, as well as the distance from the fire correlating with Ri number. Further investigations are needed to quantify these preliminary findings.

Future work

Laser sheet illumination of the flow in the vertical mid-plane along the tunnel axis has demonstrated the existence of a sharp stable interface between the cold clear air and hot smoke layers inhibiting turbulence and smoke diffusion. Low-frequency small-amplitude gravity waves have also been observed moving along this hot/cold interface, oscillating at Brunt-Väisälä frequencies. These oscillations are of course not observable in a steady-state CFD simulation; an unsteady time-dependent approach is required, where the memory and computation times are many times larger. It has long been suspected [2] that the point at which these internal waves become unstable and lead to smoke mixing with the clear air flow underneath depends primarily on Richardson number. The existence of such a critical value of Richardson number will be investigated both experimentally and computationally, by a parametric study varying the tunnel length, height, gradient, heat loss rate and fire orientation and power.

The project further aims to carefully examine the conditions at which external disturbances (e.g. tunnel road signs, traffic lights, etc.) may lead to breakdown of the stratified interface, leading to premature smoke mixing.

References

1) Armstrong J., Tabarra M., Bennett E.C., Matthews R.D. & Smith T.W. (1995), "Energy Savings in Longitudinal Tunnel Ventilation Systems", Proceedings of the Seminar on Installation Effects in Energy Savings in the Design & Operation of Fans, IMechE, pp 37-47
2) Heselden A.J.M. (1976), "Studies of Fire and Smoke Relevant to Tunnels", 2nd International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels, Cambridge, BHRA Fluid Engineering, paper J1
3) Markatos N.C., Malin M.R. & Cox G. (1982), "Mathematical Modelling of Bouyancy-Induced Smoke Flow in Enclosures", Int. J. Heat & Mass Transfer, Vol 25, No 1, pp. 63-75
4) Xue H., Hihara E. Saito T. (1994), "Temperature Stratification of Heated Air Flow in a Fire Tunnel", JSME Int. J., Series B, Vol. 37, No. 1, pp. 187-194
5) Fletcher D.F., Kent J.H., Apte V.B. & Green A.R. (1994), "Numerical Simulation of Smoke Movement from a Pool Fire in a Ventilated Tunnel", Fire Safety J., Vol. 23, pp. 305-325
6) Bettis R. (1995), "Controlling Smoke in Tunnel Fires", Fire Prevention, Vol. 280, pp. 19-22
7) Tabarra M., Kenrick B. & Matthews R.D. (1996), "CFD Validation of Natural Smoke Movement in a Model Tunnel", ASME Fluids Engineering Summer Meeting, San Diego, USA, FED-Vol. 238, pp. 543-546
8) Oka Y. & Atkinson G.T. (1995), "Control of Smoke in Tunnel Fires", Fire Safety J., Vol. 25, pp. 305-322

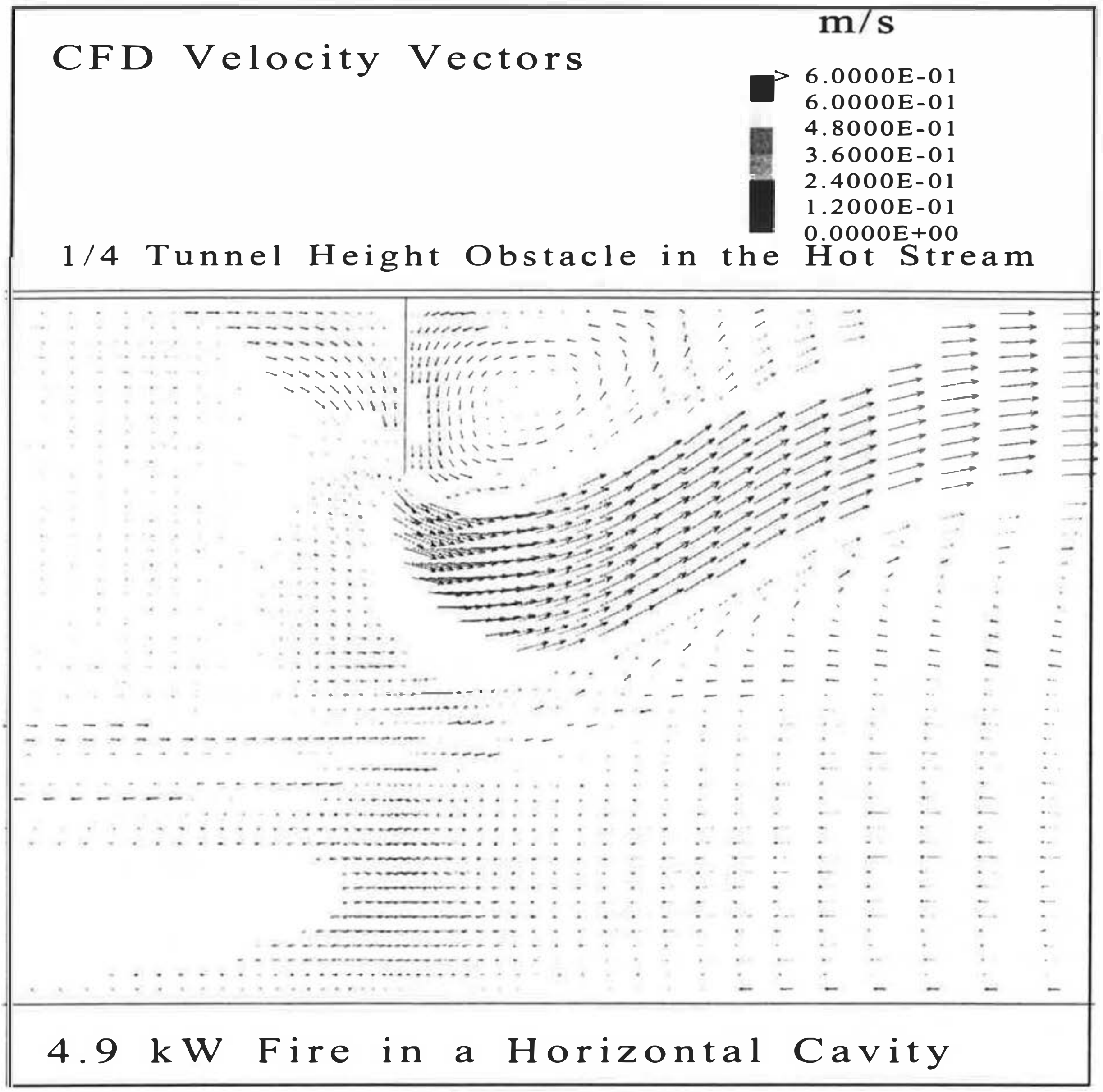

Figure 3: **CFD velocity vector plot of the flow field in the vicinity of a barrier of 1/4tunnel height placed in the hot stream 5m from the portal.** The hot stream negotiates the obstacle and maintains stratification.

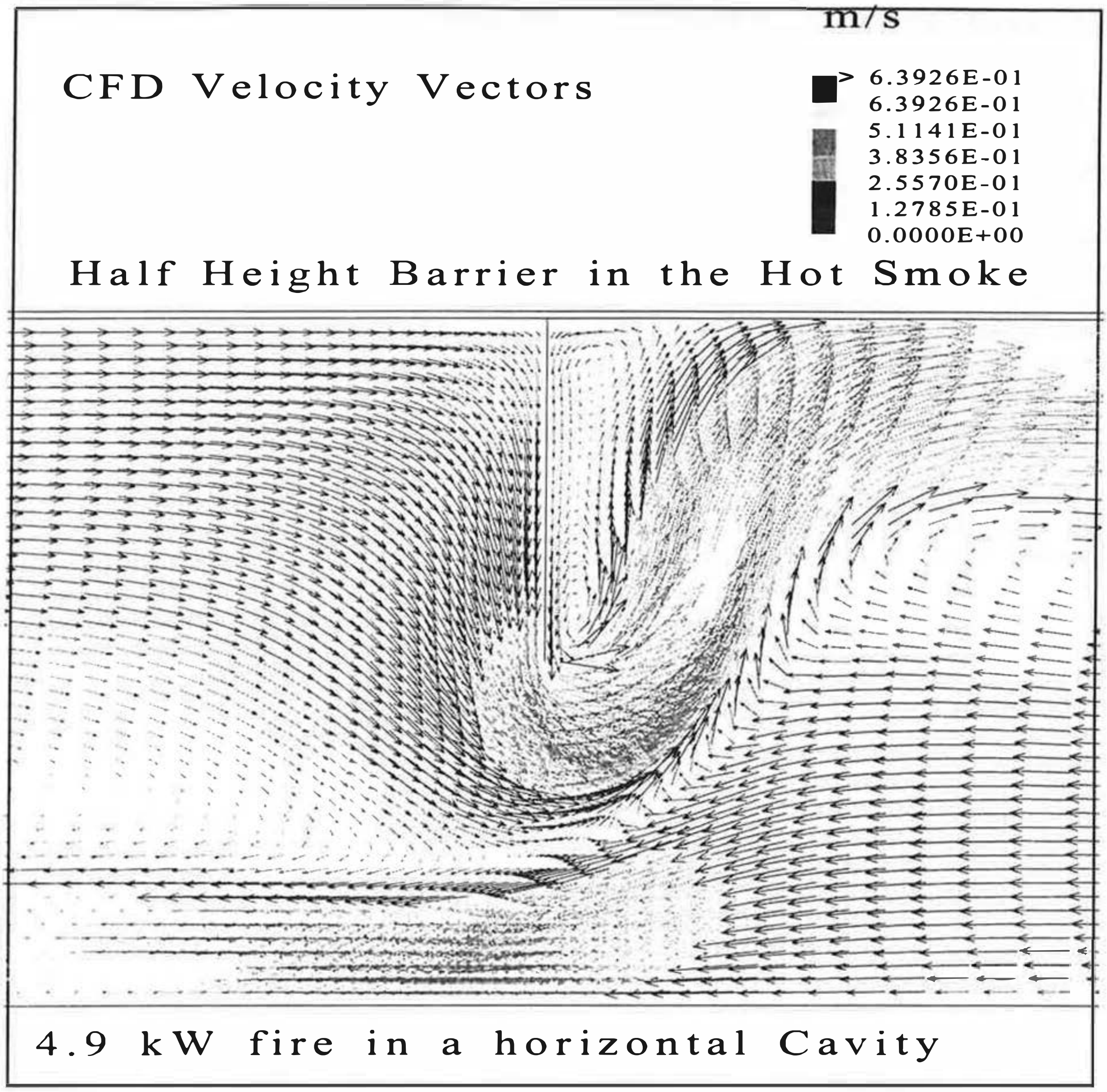

Figure 4: **CFD velocity vector plot of the flow field in the vicinity of a barrier of 1/2 tunnel height placed in the hot stream 5m from the portal.** The hot stream cannot negotiate the obstacle and severe flow disturbance leads to smoke recirculating back into the cold stream and destratification.

Investigation into heat transfer mechanisms in enclosures

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Abstract

Convective heat transfer coefficients (htc's) currently used in building thermal models have in most cases been based upon data for small, free-edge heating plates. An extensive survey of htc data has shown that a very wide variation exists in htc values for vertical and horizontal surfaces. In some cases, an htc in the range 1 - 6 W/m^2K has been found for walls depending upon the temperature difference between the surface and ambient air.

This paper presents convective heat transfer coefficients for the heated surfaces of an environmental chamber measured under controlled conditions. Using heated plates attached to an internal surface of the chamber and by accurately measuring the surface and air temperatures, the htc's were deduced after allowing for conduction and radiation losses from the plates. Data are presented for a heated wall, a floor and a ceiling for natural convection.

It has been found that the value of htc used has a significant influence on the temperature of a surface heated by solar irradiance predicted by a building thermal model.

Introduction

A literature survey (Hatton and Awbi 1995) has shown that the majority of natural convection heat transfer coefficient (htc) data available relate to free-edge heating plates. The literature has shown a wide discrepancy in the htc's. This may be partly attributed to the fact that few researchers accounted for the effect of thermal radiation in their calculations. Significant variations can also be attributed to the effect of room air movement resulting from differences in room surface temperature.

To attain accurate results, the instrumentation to be used for critical measurements, e.g., surface to air temperature difference, must be of high accuracy as only small errors can cause significant errors in the calculated htc.

Convective heat transfer coefficients are widely used in building thermal models. The majority of models utilise the coefficients relating to free-edge heating plates. The above findings therefore raise the issue of the reliability of the results generated by some thermal models which are being extensively used as design tools for building systems.

This paper presents the work that is currently underway at The University of Reading to produce an accurate measurement of htc's for the heated surfaces of a test chamber. The natural convective heat transfer coefficients for a heated wall, floor and ceiling are presented. These results are then compared with published data.

The htc results have then been used in the Arup Research & Development building thermal model "ROOM" to study the effect of the value of htc obtained from different sources on the thermal environment in a mechanically ventilated room.

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Description of the experimental set-up

The chamber has external dimensions 4.0m x 3.0m x 2.52m with an interior comprising of two compartments divided by a plywood partition (heat sink), Figure 1. The refrigeration of one compartment is provided by a compressor housed outside the chamber. The second compartment is the main experimental area with interior dimensions 2.78m x 2.78m x 2.3m ceiling height. A small box with internal dimensions 1.07m x 1.01m x 1.05m high was also required for a number of experiments to investigate the size effect on the htc's.

Heating plates controlled by a PID temperature controller were used to heat each surface of the room as required. All surface and air temperature measurements were made using PRT's with an accuracy of ~0.1K. Other measuring devices needed for the experiments included a Wattmeter to measure the power input to the heating plates, an infra red camera to measure the surface emmissivity and velocity sensors.

Determination of the heat transfer coefficient

To deduce the heat flux entering the chamber the conduction loss from the heated surface to the outside was first calculated and deduced from the power input to the plates. The radiation component of the heat flux entering the room from the heated plates was then deducted thus leaving the convective loss from the heating the plates.

The convective heat transfer coefficient could then be calculated using:

$$h_c = \frac{Q_c}{A(T_{in} - T_a)}$$

where A=Area of heated surface, m^2

T_a=Air temperature at a reference point, °C

T_{in}=Inside surface temp. , °C

h_c=Convective heat transfer coefficient, W/m^2K.

Q_c=Heat loss by convection, W

A computer program ("CHTC") developed in FORTRAN incorporates the above calculations to calculate the local and mean htc's.

Experimental programme

Before the main experimental programme could begin the emmissivity of the heating plates was required for the radiation calculations. Using an Agema 870 infra red (IR) camera, the actual emmissivity was found to be equal to 0.061 for the plates.

For each surface, the object was to calculate the htc for several air to surface temperature differences. Therefore, the plates were heated initially to 25°C and the heat sink wall cooled to 15°C. The chamber was allowed to 'run' overnight and the temperatures and the power consumed by the plates were measured and logged every 10 minutes. This process was repeated with 5K increases in the plate and a corresponding reduction in the refrigerated compartment temperature (thus reducing the heat sink wall temperature). The aim was to keep a room air temperature at ~20°C to produce the required temperature difference between the plate and ambient.

The logged data from the tests was then dissected to separate the steady state data for analysis. The htc's were then calculated using the computer program previously described.

This process was used for tests with both the chamber and small box.

Simulation test case

To calculate the thermal conditions within a single space the program "ROOM" was used for a typical day in a selected month, under dynamic thermal loading. The "ROOM" program also allowed the input of an expression for htc's into the input data.

To test the significance of the htc's for natural convection a test case was used that involved heating the floor, ceiling and wall of a room by solar irradiance. In both the wall and floor test cases, a window was positioned on the west wall (in the floor test the window was the whole of the west wall) which allowed solar patches to fall on the respective surfaces. However, an internal reflective light shelf reflected solar patches onto the ceiling. The flow rate was set to 20ac/h for each summer simulation and 10ac/h for winter simulations to counter the difference in solar gain.

The "ROOM" program uses the CIBSE average htc of 3 for all the surfaces as a default value. This value was used as a 'control' in the simulations. The rest of the calculations were conducted for a user specified htc into "ROOM" input data.

Results

Natural convection heat transfer coefficients

The following equations for the mean htc and the Nusselt number have been derived from the measurements in the chamber and small box:

Heated wall($9 \times 10^8 < Gr < 6 \times 10^{10}$):

$$h_{cn} = \frac{1.823}{D^{0.121}}(\Delta T)^{0.293} \tag{1}$$

$$Nu = 0.289(Gr)^{0.293} \tag{2}$$

Heated floor($9 \times 10^8 < Gr < 7 \times 10^{10}$):

$$h_{cn} = \frac{2.175}{D^{0.076}}(\Delta T)^{0.308} \tag{3}$$

$$Nu = 0.269(Gr)^{0.308} \tag{4}$$

Heated ceiling($9 \times 10^8 < Gr < 1 \times 10^{11}$):

$$h_{cn} = \frac{0.704}{D^{0.601}}(\Delta T)^{0.133} \tag{5}$$

$$Nu = 1.78(Gr)^{0.133} \tag{6}$$

where: h_{cn}=Natural htc, W/m^{2}K.
ΔT=Surface to air temperature difference, K.
D =hydraulic diameter, m.
Nu=Nusselt number.
Gr =Grashof number.

The htc results for tests with the chamber are plotted in Figure 2.

It is clear that the heat loss by natural convection is greater from a heated floor than it is from the other surfaces of the room. The conditions in the room for a heated ceiling are stratified, so there is little heat loss by convection. However the results from experiments using small plates (two smaller plates each with dimensions 1.01m x 0.52m wide) fixed to the ceiling show a greatly increased average htc than the large plates. The equation found from the data from the tests involving the small plates on the ceiling was:

$$h_{cn} = 1.02\,(\Delta T)^{0.16} \tag{7}$$

CFD simulations have shown that the air movement when the small plates are on the ceiling is greater than when the whole surface is heated. Therefore it appears that the conditions in the enclosure are not stratified when a small area of the ceiling is heated. This suggests that a single htc can not account for the heat transfer from a ceiling.

Comparing the measured coefficients with published data for the wall (Figure 3), it can be seen that the measured values lie between the data for an enclosure (Khalifa and Marshall 1990; Min et al.1956) and free-edge heating plate (CIBSE 1979-1986; Alamdari and Hammond 1983). Measured data for the wall are generally higher than the free-edge heating plate values. In Figure 4 the floor data show a better agreement with published data. The calculated coefficients for the ceiling shown in Figure 5 again lie within the range of published data but the scatter is much greater. The free-edge heating plate results are generally higher than Equation 5 whereas Min et al's (enclosure case) is lower. Min et al's equation was devised for a case when the whole ceiling is heated and is more comparable to Equation 5 for that reason. The free-edge plate results are closer to the small plate results (Equation 7).

A number of tests were also carried out to study the effect of a wall jet over a heated room surface. A nozzle 610mm wide, with an adjustable height was used to produce the wall jet over a heated surface. It was found that the htc increase with increasing velocity at the jet opening and/or increasing the jet opening size.

Simulation results

Each set of simulation results showed that the surface temperatures varied with the htc that was used in the calculations. The results for mid-day July with the sun entering the room through a south-facing glazed wall and falling over the floor, is plotted. Figure 6 shows that for some 'hot spots' on the floor, a surface temperature difference of about 13K is predicted by the "ROOM" program depending on the value of htc used. The difference between our htc results and those for htc = 3 are the largest but it is only about 2-3K from the ASHRAE values. Although some of the temperatures involved are too high for comfort, the dry resultant (Tres) predicted does not vary much with the value of htc because of the large ventilation rate used.

These results show that differences in surface htc's do have an effect on the results predicted by building thermal models.

Conclusions

The natural convection results show that the measured htc lie within the wide range of data given in the literature for free edge plates and room surfaces. The results are represented by Equations (1) to (6).

The size of the actual heated plate only really made a difference when placed on the ceiling. The small plate htc's were significantly higher than those from the large plates.

The simulations have shown that different htc's used in the "ROOM" program produce different surface temperatures. A maximum difference of 16% was obtained for the temperature of a sun patch on the floor of a small room. As the heat transfer coefficient clearly influences the surface temperatures of a building then it can be said that the air temperature and thermal comfort would also be influenced.

A wall jet was found to increase the htc for the heated surfaces on the chamber. The mixed convection htc is also influenced by the width of the slot.

Equations (1) - (6) are recommended for use in building thermal models for natural convection based scenarios. However, further work is recommended to study in more detail the effect of size of the heated area on the htc for a ceiling.

Acknowledgement

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References

Alamdari, F. ; and G.P Hammond. 1983. Improved correlation's for Buoyancy-driven convection in rooms, Building Serv. Eng. Res. Technol., Vol.4, No3, pp.106 - 112.

ASHRAE. 1981. 1981 ASHRAE Fundamentals, Atlanta: American Society of Heating Refrigeration and Air-conditioning Engineers, Inc.

CIBSE. 1979 and 1986. CIBSE Guide, Section A5 and A9, Chartered Institute of Building Services Engineers, London.

Hatton, A.; and H. Awbi. 1995. Convective heat transfer coefficients of room surfaces, IMechE Conference Transactions, London. pp.201-206.

Khalifa, A.J.N.; and R.H Marshall.1990. Validation of heat transfer coefficients on interior building surfaces using a real - sized indoor test cell, Int. Journal of Heat and Mass Transfer, Vol.33, pp.2219 - 2236.

Min, T.C.; L.F. Schutrum; G.V Parmelee; and J.D. Vouris.1956. Natural convection and radiation in a panel heated room, ASHRAE Trans, Vol.62, pp.337 - 58.

Figures

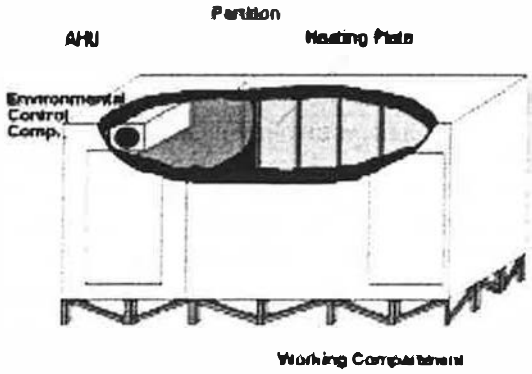

Figure 1. Environmental chamber

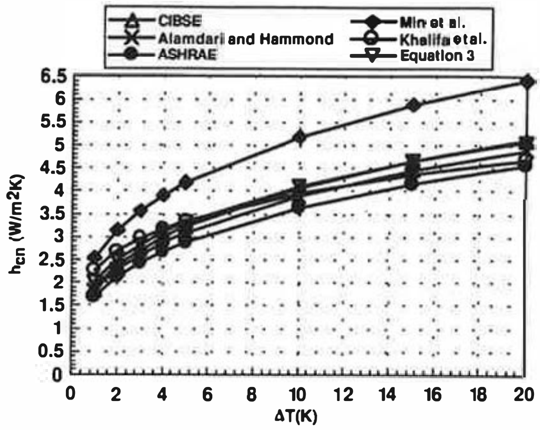

Figure 4. Comparison of floor data

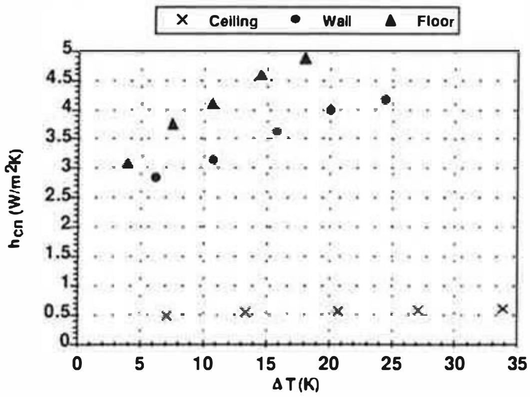

Figure 2. Natural convection htc's found using the chamber.

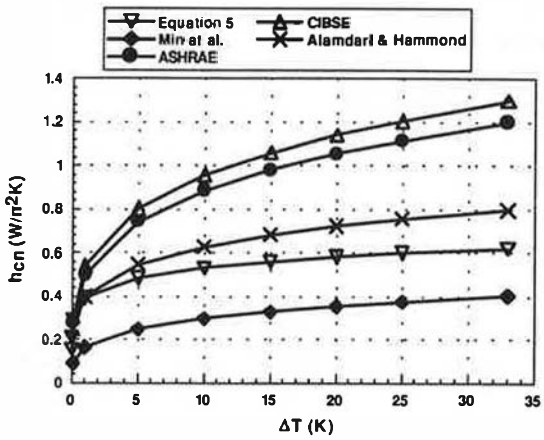

Figure 5. Comparison of ceiling data

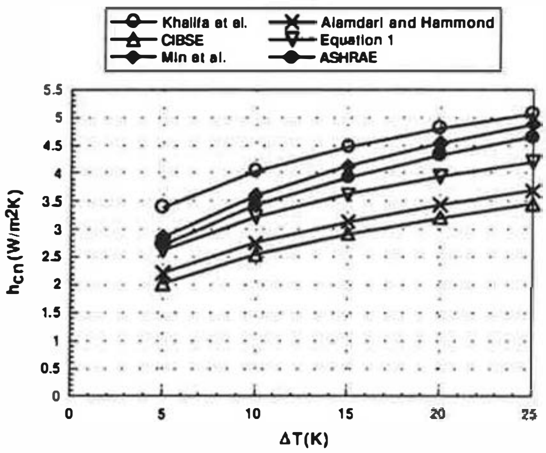

Figure 3. Comparison of wall data.

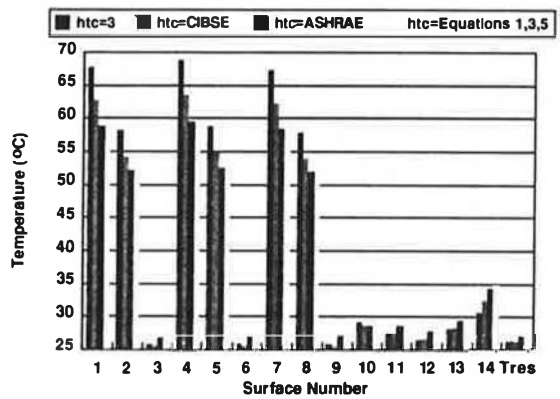

Figure 6. Comparison of the floor surface temperatures predicted for a room with sun patches at 12pm in July. Surface numbers 1-9 denote values for 9 areas on the floor, 10-14 denote the remaining 4 walls and ceiling.

On the modelling of diffuse reflections in room acoustics prediction

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Summary

Partial diffraction and scattering play an important role in the reflection of acoustic waves by a real-life wall surface. In the modelling of the acoustic sound fields inside an enclosed space, the incorporation of such diffraction and scattering effects can greatly improve the accuracy of the modelling. In commonly used room acoustics prediction models, such as the image or the ray tracing methods, these effects are approximated by partial diffusion - by augmenting specular reflections with the so-called diffuse reflections. The fraction of acoustic energy that is reflected diffusely upon a wall reflection is related to a diffusion coefficient of the wall. Currently there are a number of different methods available to implement diffuse reflections in room acoustics prediction models, and there is no single accepted way of defining the diffusion coefficient for a wall surface. This paper investigates the prediction characteristics of three commonly used diffuse reflection modelling methods and attempts to establish the diffusion coefficient values of some common room surfaces. It also looks at the possibility of calculating the diffusion coefficient from the polar diffraction pattern of a surface and some means of measuring the coefficient.

Introduction

The diffusion of sound, just as the absorption of sound, is an inevitable part of a wall reflection. Sound diffusion in this case is a general description of the total effect of sound diffraction and scattering which diverts energy away from the specular reflection direction. In recent years it has become increasingly obvious that this sound diffusion effect at wall reflections needs to be included in the computer modelling of built environments, especially in disproportionate factories and in large concert halls, in order to achieve reliable prediction results [**1,2,3**]. In most computer models, the diffusion effect is modelled by the incorporation of diffuse reflections in addition to the usual specular reflections, with the proportional amount of diffuse reflections given by a diffuse reflection coefficient of the wall. However, unlike sound absorption at a wall which is characterised by the well-established sound absorption coefficient, the characterisation of sound diffusion at wall reflections is not well established. The definition of the diffuse reflection coefficient of a wall is unclear and there is no single standardised method to calculate or to measured the value of this coefficient. As a result there are a great variety of methods of modelling diffuse reflections in computer models [**4**] and various values of the coefficient have been suggested. Since the theoretical basis of these methods of modelling diffuse reflections may not the same, it is likely that they may require different values of diffuse-reflection coefficient even for the same wall under the same room condition. Clearly there is a need for a deeper understanding of diffuse reflections in order to standardise the diffuse reflection coefficient and to find the most suitable way of using it in computer models. This paper represents the first step towards this goal. Three existing methods of modelling diffuse reflections is compared under various room conditions to establish their similarities and differences. The result will be used to establish the likely values of the diffuse reflection coefficient for some common wall surfaces. Possible methods for calculating or measuring the coefficient directly from a surface's reflection pattern will also be examined.

Methods of modelling diffuse reflections

Secondary randomized diffuse rays model

The first method is the one implemented by Hodgson based on a ray tracing model [**3**]. The method itself is a ray scattering process suggested by Kuttruff [**5**]. A wall is considered to reflect a proportion, equals to the diffuse-reflection coefficient d, of all the incident sound energy diffusely, and the remaining proportion 1-d specularly. The direction of a diffuse reflections is determined by random numbers. Data published in ref.[**3**] is used here to represent the prediction behaviour of this method.

Table 1 RT(s) at 630Hz predicted by different diffusion methods.

Diffuse-reflection coefficient d	Room 1: 27.5mx27.5mx27.5m			Room 2: 110mx55mx5.5m		
	Hodgson*	ODEON 2.5	SU-Model	Hodgson*	ODEON 2.5	SU-Model
d=0	9.16	9.20	9.18	13.41	11.96	11.90
d=0.1	/	8.89	8.65	/	7.40	6.60
d=0.25	8.89	/	/	6.57	5.98	5.20
d=0.5	8.89	/	/	5.84	5.45	/
d=0.75	8.89	/	/	5.65	5.19	/
d=1	8.89	8.98	8.64	5.55	5.10	5.0
Eyring	8.8			5.0		
Measured	**8.7**† (8.89*)			**5.4**† (5.52*)		

* from Table II of Hodgson, J.Acous.Soc.Am. **89**(2), p.768 (1991).
† from Figure 2 of Hodgson *et al*, J.Sound and Vib. **113**(2), p.260, (1987).

Randomized ray directions model

The second method is that of the commercially available hybrid image/ray tracing model ODEON Version 2.5 [**6**]. The calculation is separated by a user-defined transition order, TO, of reflection into two parts; early and reverberant. Reflections with orders lower than the transition order are purely specular. From the transition order on sound rays are treated as energy packets as in a normal ray tracing method but with the ray direction randomized according to the diffuse reflection coefficient. One potential problem with this approach is that the concept of a transition order is not physically satisfactory since diffuse reflections should occur even at the very first reflection rather than suddenly being switched on at the transition order.

Modified scattered diffuse energy model (su-model)

A common feature of the above two methods is that the diffusely reflected energy is represented by randomized ray reflection directions, and they only have a statistical correspondence with the scattered energy. In the third method the diffuse-reflection coefficient is used to define the fraction of energy diffusely scattered into non-specular angles, while the remaining energy is reflected specularly in the usual way. The diffuse energy is then assumed to decay exponentially. This concept has been used before [**7,8**]. However there is one main drawback in this model - the diffuse energy is assumed to be uniformly distributed to all receivers and the effects created by the presence of shielding surfaces such as balconies cannot be accounted for. The method is modified here by the introduction of initial secondary diffuse sources and late area weighted shielding to overcome this problem [**9**]. The modified method is labelled "SU-Model" in this paper.

Comparisons of methods

Perfectly rectangular 1:50 scale rooms

Two of the rectangular physical scaled models used by Hodgson [**3**] were used to provide a convenient starting point for our comparisons. The first, Room 1, was a cubic room of size 27.5m x 27.5m x 27.5m. In here all the scale model parameter values are given in their full-size equivalents. The second, Room 2, was of size 110m x 55m x 5.5m which represented a highly disproportionate factory. The rooms were made of varnished plywood. The acoustic data measured on these rooms were taken from ref.[**10**]. Table I compares the predictions of these rooms' reverberation times (RTs) at 630Hz. In the case of the cubic Room 1, all three methods produced similar results and the effect of diffuse reflections was small in proportionate rooms with a single wall type. In the highly disproportionate Room 2 the effect was much more pronounced. The convergence rates of the three methods were also different. Hodgson's prediction converged to the measured value at *d*=1, while ODEON 2.5 and SU-Model predictions converged to within 2% of the measured value at about *d*=0.5 and *d*=0.25 respectively. The result confirms that the value of *d* of a wall generally changes with the shape of the room, and in extreme cases (i.e. highly disproportionate rooms) the degree of change becomes significantly dependent on the method of diffuse reflection calculation used.

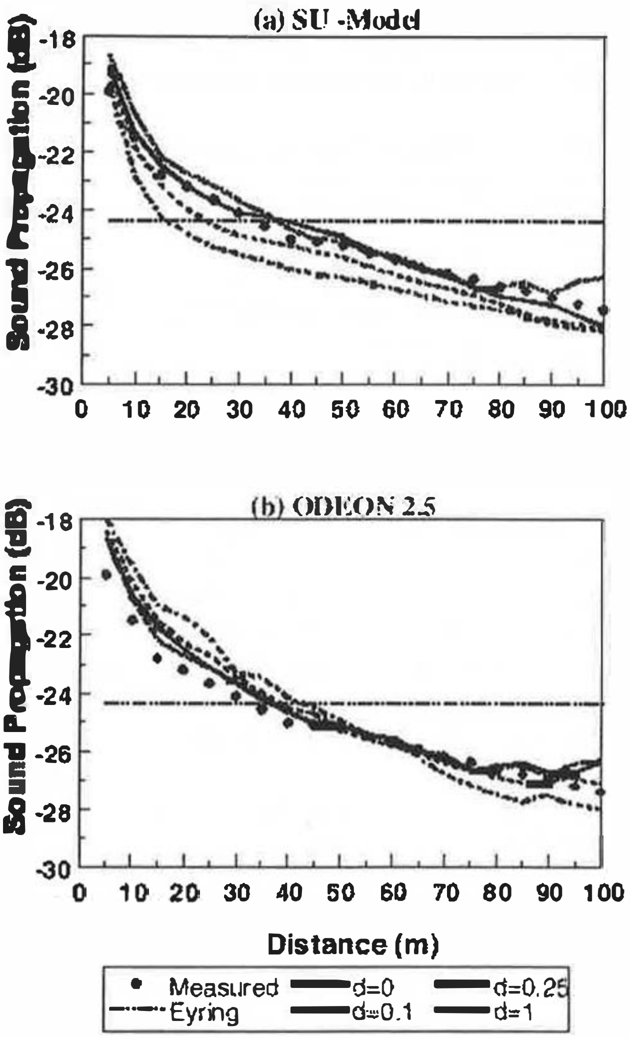

Figure 1 Predicted sound propagation at 630Hz in a 110mx55mx5.5m perfectly rectangular room. Measured data taken from Figure 8 of Hodgson *et al*, J.Sound and Vib. **113**(2), (1987), p.264.

Similar trends were also observed in the sound propagation (the variation with distance of the steady state sound pressure level minus the source sound power level) curves in the rooms. In Room 1 the curves were very much the same at all values of *d*. In the disproportionate Room 2 the variation with *d* was significant but the value of *d* at which best-fit occurs is similar for all three methods. In ref.[**3**] Hodgson's prediction best matched the measured curve at around *d*=0.26, which was similar to the *d* values at which the ODEON 2.5 and SU-Model predictions best matched the measurement (see Figure 1). The variation of sound propagation curves with *d* predicted by ODEON 2.5 is in fact similar to that predicted by Hodgson's model in Ref.[**3**].

A full-size real multi-purpose auditorium

The real hall used for this investigation was a fan-shaped, multi-purpose auditorium which was used primarily for lectures and concerts. The size of the hall was about 10500m^3. An outline of the hall is shown in Figure 2. The Figure also shows the arrangement of the stage and side balconies in dotted lines, and the overhead reflectors in dashed lines. The source and receiver positions are also shown. The source used for the measurement was a decahedron source which was omni-directional up to about 2kHz. The impulse response at each receiver was measured by a maximum length sequence system [**11**].

In the computer modelling, typical sound absorption coefficient data of materials closely matching those of the wall surfaces found in the hall were used. Using these data, the reverberation time was predicted to within 3% of the measured value at 1 kHz.

Figure 3 shows the predictions of Clarity Index C80 in the 1 kHz band in this hall using different *d* settings. C80 is related to the subjective clarity of a hall and is defined as

$$C80 = 10 \cdot \log_{10}\left\{\frac{\int_{0}^{80ms} E(t)\,dt}{\int_{80ms}^{\infty} E(t)\,dt}\right\}$$

where E(t) is the energy of the impulse response at the receiver. Unlike the reverberation time and sound level which are mainly dependent on the overall sound decay in a room, C80 is also strongly dependent on the distribution and magnitude of the earlier reflections (within 80 ms after the arrival of the direct sound) and its prediction is therefore more affected by the diffuse reflection modelling.

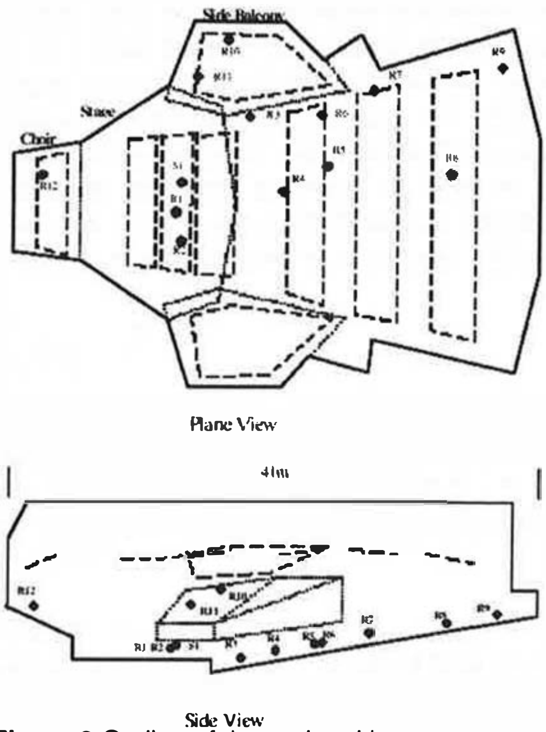

Figure 2 Outline of the real multi-purpose auditorium. Dotted lines indicate the stage and side balconies. Dashed Lines indicate the reflectors

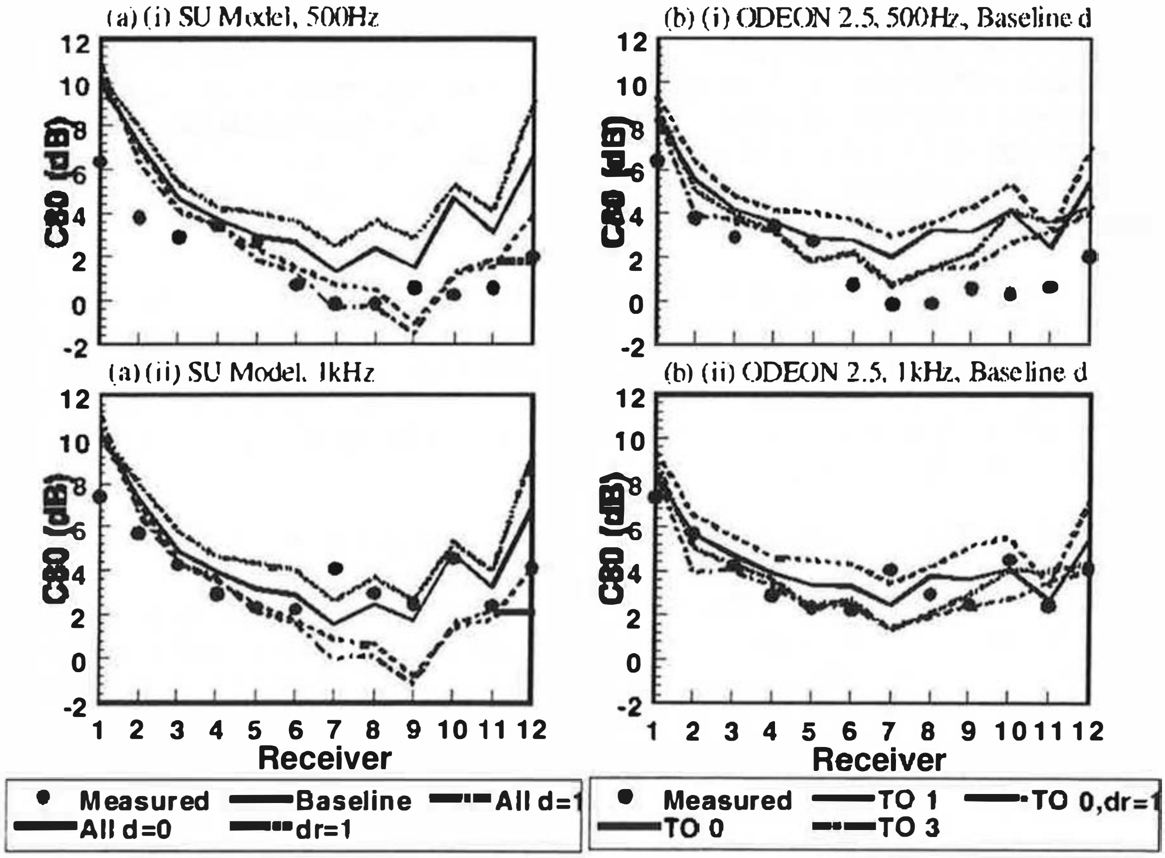

Figure 3 Comparison between C80 predictions in the real multi-purpose auditorium. Predictions used the 'baseline' diffuse-reflection coefficient setting unless otherwise stated

One setting of *d* shown was that with the diffuse-reflection coefficient for the reflectors *dr* set to **1** but otherwise the same as a baseline setting of *dw*=0.1 for all the plain surfaces and *ds*=**0.7** for the seating. The effect of the *d* setting can be clearly seen. In the case of SU-Model, the baseline diffuse-reflection coefficient setting gave the best prediction at 1 kHz. Also shown is the 500 Hz octave band results in which the modified setting with *dr*=1 gave much better predictions at receivers 6 to 12. This was because the reflectors were less effective in producing specular reflections at low frequencies. Rindel [**12**] used an approximation of the Fresnel integral to derive a cutoff frequency f_c below which the specularly reflected energy from a plane reflector drops significantly:

$$f_c = \frac{c}{2(W\cos\beta)^2}\left(\frac{2d_s d_r}{d_s + d_r}\right)$$

where c is the velocity of sound, d_s and d_r are respectively the source and receiver distances to the geometrical reflection point, is the angle of reflection relative to the normal of the reflector, and W is the width of the reflector. From the geometry of the hall, it was estimated that the first order specular reflection generated by the ceiling reflectors at receiver 8 would had a cut off frequency at around 690 Hz.

With ODEON 2.5 the combination of TO=1 with the baseline diffuse-reflection coefficient setting also gave the best predictions in the 1kHz band. In the 500 Hz band setting the diffuse-reflection coefficient of reflectors *dr* to 1 is again necessary to predict the reduced specular contribution from the reflectors to the receivers at the rear of the hall. Even so the accuracy is still slightly worse than that of SU-Model.

Conclusions from comparisons

The comparisons have shown that different methods of modelling diffuse reflections can have different prediction behaviours in the extreme case of highly disproportionate rooms such as factory spaces. However they remain similar in rooms with small aspect ratios that are typical of performance spaces. In this latter case a diffuse reflection coefficient value of 0.1 for varnished wood in scale models and for large plain surfaces in real halls and a value of 0.7 for both model and real hall seating have been found to be generally appropriate in the 1 kHz octave band. For plane reflectors it was found necessary to increase their diffuse-reflection coefficient value to 1 in the lower frequency bands in which their effectiveness in providing specular reflections is low.

Overall the scattered diffuse energy model has been found to be the most predictable and the most consistent in its requirement of diffuse-reflection coefficients. The difficulty with the randomized ray direction model ODEON 2.5 was the choice of the transition order, which is a software limitation particular to ODEON 2.5 and has no direct physical equivalence in real life. This order was found to be critical in the prediction of acoustic parameters that are defined by the early part of the impulse response, such as the Clarity Index C80.

Simple diffusion modelling methods, represented by those investigated here, can only adequately approximate the complex real life effects when averaged over a sufficient number of reflections. They are more likely to go wrong when predicting acoustic features that are highly dependent on the very early part of the impulse response where reflections are few and distinct. It has been seen in this paper that the prediction error increased with an acoustic parameter's dependence on the early reflections. The error margin was generally larger in C80 than in sound level. This was particularly so in models that used randomized ray directions to simulate the distribution of diffuse energy, since such a statistical simulation is valid only when a large number of reflections is involved. In our study the diffusion method that models the scattered diffuse energy directly, i.e. the scattered diffuse energy model (SU-Model), seemed to have better accuracy than the randomized ray directions models in predicting the early energy parameters.

Determination of diffuse reflection coefficient

The differences between the predictions of different diffuse reflection modelling methods are caused by the differences in their theoretical assumptions. However it is difficult to judge which of these assumptions are more correct without first defining the correct physical interpretation of the diffuse reflection coefficient. At the moment the coefficient is chosen empirically by best-fitting prediction to measured results. This means that the coefficient value is inherently dependent on the prediction algorithm used in the best-fitting procedure. Clearly, there is a need for a physically based definition of a diffusion coefficient which can be directly measured and predicted for surfaces found in rooms in order to clear up this confusion. This will enable the many varied diffusion modelling methods in different computer models to be evaluated and refined from a fundamental basis and so increase the reliability of these models.

Scattered pressure distribution based calculation

In recent years a number of investigations [see e.g. **13,14**] have produced several methods of calculating a diffuse reflection parameter from the polar distribution of scattered pressure from a surface. The polar distribution can be predicted (thus providing a totally predictive means of determining the diffuse coefficient) or can be measured. There are basically two ways of obtaining a diffusion parameter from the polar distribution. The first is based on the deviation of the polar response from a pre-defined ideal diffuse reflection pattern. The deviation can be calculated from various measures, such as the standard deviation, root-mean-squared error, or the auto-correlation function, which can in turn be based on sound energy or pressure. This approach is more suited to producing a parameter that is used to rank the "diffuseness" of a surface rather than for computer modelling since the parameter value so produced is generally not bounded between 0 and 1 and there is no direct indication to the share between specular and non-specular energy which is required in computer modelling. The second approach is based on the ratio of the average specular zone energy to the total scattered energy. Its concept is compatible with some of the diffusion modelling methods currently used in computer models but has a conceptual problem in the definition of the specular zone, which changes size depending on source and receiver positions. Figure 4 shows a comparison between the values of the coefficient of a curve panel calculated by examples of these two approaches and that determined semi-empirically by best-fitting the computer model predicted changes to the measured changes in the reverberation time in a non-diffuse room due to the introduction of the surface. In this case the coefficient based on the energy deviation approach correlates quite well with that determined empirically by computer modelling. The coefficient based on specular zone suffers from the uncertainty in the definition of the specular zone. In Figure 4 the specular zone is chosen as that given by an equivalent flat panel. Since the curve panel always reflected most of the energy away from one single direction, the energy in the chosen specular direction is small and the coefficient is apparently close to 1 at all frequencies. This highlights one of the main problems with this approach in that, a surface that diverts energy away from the pre-defined specular direction into another focussed direction will have a high diffuse reflection coefficient even though the energy is not uniformly or diffusely distributed to all directions.

For plane and curved panels the energy deviation based approach and the computer modelling seem to agree fairly well on the value of the coefficient. However on other more complicated surfaces the correlation is less satisfactory. Clearly there is much to be done before a coefficient that can satisfied all requirements can be defined. This is indeed the subject of a EPSRC funded project currently being carried out at Salford.

Direct measurement of non-specular energy

Mommertz [15] recently introduced a method which directly measures the amount of energy scattered from the specular direction from rough or structured surfaces. By monitoring the changes in the impulse response of a surface due to variation of the positioning of the surface relative to the source-receiver configuration, the specular energy (invariant) and the diffuse energy (variant) can be separated out. The diffuse reflection coefficient can then be directly calculated. The advantage of this method is that it is a direct measurement and does not rely on any prediction and is relatively free from pre-defined assumptions. However in its current form it is limited by its assumption that the specular energy is invariant to the positioning of the surface. It will therefore have difficulties dealing with finite size panels where edge effect is significant and surfaces which re-direct rather than diffuse the reflected energy.

Semi-empirical determination of coefficient [16]

The result of the comparisons between computer modelling methods shows that the coefficient determined empirically by best-fitting prediction to measurement is not sensitive to the modelling method chosen for the prediction provided that the room is not too disproportionate. This suggests that one can devise a semi-empirical method of determining the coefficient of a surface by best-fitting the computer model predicted changes to the measured changes in the diffuseness of a non-diffuse room due to the introduction of a surface. The coefficient thus produced is inherently for use in computer modelling. Provided that the room is proportionate, the coefficient can be used by other modelling methods.

The advantage of this semi-empirical approach is that it is simple and uses procedure and facility that are similar to that used for the measurement of sound absorption coefficient. The non-diffuse room can be obtained by putting carpet into a otherwise empty reverberant room. The sound field will be non-diffuse because of the concentration of absorption on one surface - the carpeted floor. The changes in the diffuseness of the room can be monitored by measuring simply the reverberation times of the room with and without the diffusing surface. The diffuse reflection coefficient can then be determined by choosing a value that gives the correct reverberation times in the computer model prediction. Further more, since diffuse reflection is dependent mainly on the geometry of a reflective surface, the measurement procedure can be carried out in physical scale models and small surface samples can be used.

This method's dependence on computer modelling predictions is its biggest weakness - the coefficient produced is related to the physical scattering properties of surfaces only through the interpretation of the computer model whose accuracy is still questionable. There are also details about the requirements about the size, shape etc. of the measurement room and the surface sample to be resolved. The result shown in Figure 4 was obtained in

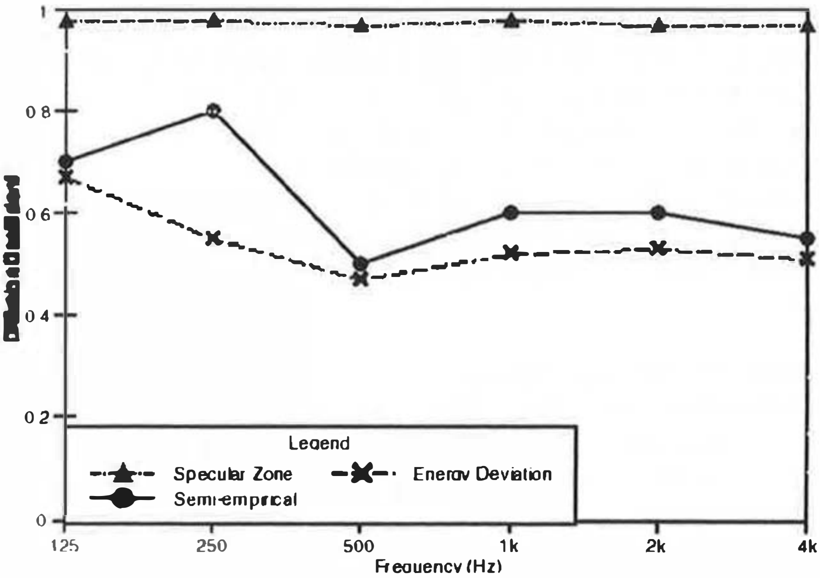

Figure 4 Diffusion coefficients of a curved panel determined by various methods.

a 1:10 scale rectangular room of full size dimensions of 11 m x 7 m x 4 m. The result is very promising. Further investigation will be carried out during our EPSRC funded research in the next 3 years.

Conclusions

Diffuse reflections has been shown to be an important factor in the modelling of sound fields in enclosed spaces. Since different methods of modelling diffuse reflections can produce significantly different results in factory-like disproportionate rooms, there is a need for a rigorous physically based definition of the diffuse reflection coefficient so that the suitability of these methods can be assessed. Even in proportionate rooms where the differences between methods are small, the need for a defined method to determined the coefficient from the physical scattering properties of a surface still remains. The development of such a definition will further our understanding of the computer modelling of diffuse reflections, and provide the industry means of measuring or predicting the coefficient. This paper presents the result of our preliminary investigation into the determination of the diffuse reflection coefficient which shows the promising potentials of several methods. The investigation will continue for the next three years in a EPSRC funded research project.

Acknowledgements

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References

1. Kuttruff H., *ROOM ACOUSTICS*, 3rd Ed., (Elsevier Science Publishers Ltd., London, 1991), Chap IV, p.84-85.
2. Lam Y.W., Referred Paper, Proc. IOA **16**(2), 537-544, (1994).
3. Hodgson M., J.Acous.Soc.Am. **89**(2), 765-771, (1991).
4. Dalenbäck B., Kleiner M., Svensson P., J.Audio Eng. Soc. **42**(10), 793-807, (1994).
5. Kuttruff H., Acustica **25**(6), 333-342, (1971).
6. G.Naylor, 124th Acous.Soc.Am. Meeting, Paper 3aAA2, New Orleans, (1992).
7. Rietschote H.F., Houtgast T., and Steeneken H.J.M., Acustica **49**, 245-252 (1981).
8. Nakagawa K., Miyajima T., and Tahara Y., Appl. Acoust. **38**, 115-129 (1993).
9. Lam Y.W., J.Acous.Soc.Am. **100** 2181-2192, (1996)
10. Hodgson M.R., Orlowski R.J., J.Sound and Vib. **113**(2), 257-271, (1987).
11. Rife D.D. and Vanderkooy, J.Audio Eng. Soc. **37**, 419-444, (1989).
12. Rindel J.H., Proc. of Nordic Acoustical Meeting 1986, 257-260, (1986).
13. T.J. Cox, J.Acous.Soc.Am. **97**, 2928-2936 (1995).
14. D'Antonio P. and Konnert J.H., J.Audio.Eng.Soc. **40**, 997-1017 (1992).
15. Mommertz E., Proc. 15th ICA Vol.II, p.577-580, (1995)
16. Pantelides A.C., MSc Thesis, University of Salford, (1995)

Thermal comfort requirements for people with physical disabilities

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Summary

A Laboratory study was conducted to compare the thermal comfort responses of male and female subjects with and without physical disabilities. An additional aim was to determine whether existing methods and standards (Predicted Mean Vote-PMV. (Fanger 1970, ISO 7730 1994)) were appropriate for determining comfort conditions for people with physical disabilities. Thirty two subjects participated in three, three hour experimental sessions in a simulated 'living room'. Eight males and eight female subjects with and without physical disabilities were investigated in balanced groups of eight. The three thermal conditions correspond to 18.5^{O}C, PMV = -1.5, slightly cool to cool; 23^{O}C, PMV = 0, neutral; 29^{O}C, PMV = +1.5, slightly warm to warm. Subjective ratings of thermal sensation, comfort, preference, stickiness, dryness and draught were recorded every fifteen minutes throughout the experiment. The physical disabilities of subjects included: cerebral palsy, spina bifida, stroke, friedrichs ataxia, blind, paralysis, heart condition, encephalitis, gilleaw barrie syndrome, missing limbs, metal work in legs.

The results showed no significant differences (p >.05) between the mean responses of subjects with physical disabilities and those without There were no interactions found between the gender and the population group. Variation in responses was greater for people with physical disabilities than those without for slightly cool to cool and neutral conditions but was less for slightly warm to warm conditions. On average therefore it was concluded that there were no differences in responses between all groups tested.

A 'case by case' analysis identified differing requirements for individual subjects and types of disability. It was concluded that, at present, when introducing people with physical disabilities into working environments their thermal comfort requirements should be considered on an individual basis. It is also suggested that further research is required to identify if there are any subgroups of the population, 'people with physical disabilities', that have similar thermal comfort needs.

Aim

This study has three aims:

To compare the thermal comfort requirements of people with physical disabilities with those of people without physical disabilities.

To compare the thermal comfort requirements of males and females.

To identify if present comfort standards as set by Fanger's thermal comfort model (Fanger 1970, ISO 7730 1994) can be used to predict comfort conditions for both people with and without physical disabilities.

Introduction

Thermal comfort requirements have been the topic of much formal laboratory and 'field' research for over one hundred years and much is known about comfort conditions for "able bodied" workers in

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indoor environments. Little is known however, about requirements for people with physical disabilities. That is in terms of whether requirements are significantly different from those of people without physical disabilities, whether current methods used to establish comfort conditions are appropriate for people with physical disabilities and the extent to which deviations from comfort conditions affects the degree of discomfort of people with physical disabilities. The answer to these questions may depend on the type of physical disability, but this is also not known. The aim of the laboratory experiment presented in this paper was to address the above questions for both male and female subjects. The results are intended to provide insight into thermal comfort requirements, issues and paradigms relevant to a range of people with physical disabilities.

Thermal comfort has been defined as "the condition of mind that expresses satisfaction with the thermal environment" (ISO 7730 1994). The reference to "mind" emphasises that comfort is a psychological phenomena. It is therefore often "measured" using subjective methods. Over many years empirical research has related environmental conditions to physiological and subjective responses of subjects. Rational analysis using equations for heat transfer between the clothed human and the environment have been combined with empirical thermal comfort research to produce established methods for predicting the thermal comfort, and degree of discomfort, of people exposed to a wide range of environmental conditions. This is the basis of the predicted mean vote (PMV) thermal comfort indices of Fanger (1970), which are now accepted as BS EN ISO 7730 (1995).

The PMV is the predicted mean vote of a large group of people exposed to the thermal conditions of interest and providing a rating on the following scale:-

+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

For example if the average sensation over the large group of people was 'slightly warm' then the PMV would be +1. The predicted percentage dissatisfied (PPD) is related to the PMV and is based upon the individual variation in response for a given set of conditions. A value of PMV=0 is neutral and said to provide comfort conditions with an associated PPD of 5%. A PMV = +1 or -1 provides a PPD of around 25% and so on.

The PMV/PPD are calculated from a knowledge of the so called six basic parameters. These are: air temperature, radiant temperature, air velocity and humidity of the environment as well as the clothing and activity level of the people. The method was developed using college students from the USA and Denmark but comparisons have also been made with the responses of the aged and for both males and females. There has been little research into people with physical disabilities.

People with physical disabilities may differ in their comfort requirements from people without physical disabilities for a number of reasons. It may be that the disability interferes with the thermoregulatory responses of a person such that vasoconstriction or vasodilatation reactions are affected, skin temperatures may then be abnormally high or low. Sweating may also be affected as may shivering and other responses. The method for coping with a disability may also be important. For example some drugs will affect the thermoregulatory system and technical aids such as wheelchairs or artificial limbs may have consequences for thermal comfort requirements. Psychological issues may also be important. Restriction in the ability to move or react in another way may make deviations from thermal comfort conditions more threatening than for those with full mobility.

There has been some research into the thermal comfort of people with physical disabilities. These studies have largely been conducted in Japan and Hungary. Yoshida, et al (1993) report a joint Hungarian and Japanese study where fifteen people with physical disabilities were exposed to a variety of thermal conditions in a thermal chamber. It was concluded that there were differences in thermo-physiological responses between the disabled group and a control group. Risks of overheating due to restricted sweating responses and overcooling due to disorders of the peripheral blood flow, were reported. Other relevant studies have been conducted into computer modelling of human responses (Yoshida, et al 1989) and into the relationship between cerebrovascular disease and indoor environments (Yoshino, et al 1993). Giorgi, et al (1996) provided a review of "Responses of Disabled People to Thermal Environments". Despite much information, they found a general lack of data on thermal responses that could usefully be used to determine thermal sensation and comfort conditions They found that "physically handicapped persons (poliomyelitis, anterior acuta, infantalis cerebralis paresis, paraplegia, spina bifida and quadriplegia) demonstrate thermoregulatory abnormalities in the affected portion of their bodies". They suggested that further data were required to understand the categories of population studied.

Method

The methodology was based upon that of an earlier study by Breslin (1995) which compared the thermal comfort requirements of males and females.

In the present experiment thirty two subjects were each exposed to three different thermal environments of 18.5^{O}C, PMV = -1.5, slightly cool to cool; 23^{O}C, PMV = 0, neutral; and 29^{O}C, PMV = +1.5, slightly warm to warm. Of the thirty two subjects sixteen people had physical disabilities and sixteen people did not have any physical disabilities. In each of these groups of sixteen people, eight were female and eight were male. Environmental data and subjects subjective data were recorded every fifteen minutes over a three hour period. This protocol was similar to the original experiments used to derive the PMV/PPD methodology, Fanger (1970).

Subjects characteristics of age, height and weight were recorded for all thirty two subjects. The subjects with disabilities were a heterogeneous group. The disabilities that people had are as follows:

Blind/Heart Condition/Diabetic	Cerebral Palsy
Stroke/Brain Surgery	Neck Injury - RTA*
Encephalitis	Gilleaw Barrie Syndrome
Weakness Left Side - RTA*	Cerebral Palsy/Addisons Disease
Metal Work in Legs - RTA*	Paralysis/Epilepsy - RTA*
Spina Bifida	Blind - RTA*
Multiple Sclerosis	Walking/Sight Problems/Diabetic
Friedrichs Ataxia	Missing Lower Arm

* RTA This indicates where the disability is as a result of a Road Traffic Accident.

Procedures

All prospective subjects were given an explanation of the procedure in writing, and verbally where requested. Before the start of each experimental session all subjects completed a medical form and a consent form. Oral temperatures using mercury in glass clinical thermometers were taken every session.

The procedure was given Ethical Clearance by Loughborough University Ethical Advisory Committee on 29th February 1996, under the Human Biological Investigations Research Protocol.

Experimental design

The subjects were divided into four groups of equal combinations of people with and without disabilities and male and females. The groups were exposed to the three conditions defined by following an incomplete blocks, four by four Latin square design.

The subjects all wore the same clothing to achieve an estimated clo value of 1.0clo. The clothing ensemble consisted of a shirt, trousers, sweatshirt, cotton underwear, cotton socks and leather shoes.

Environmental conditions.

The environmental conditions for the study were set using Fanger's (Fanger 1970) Thermal Comfort Model to achieve predicted mean votes of -1.5, 0, +1.5. Table 1 Shows the six parameters plus partial vapour pressure for each of the stated PMV's to be achieved and the actual deviations throughout the experimental sessions.

Table 1 Environmental conditions - target and deviation (For ta and rh).

PMV	-1.5	0	+1.5
Clo	1 ($0.155m^2C/W$)		
Activity	Sitting at rest. ($58W/m^2$)		
t_g =	ta		
v =	0.15m/s		
t_a	$18.5^oC \pm 0.6$	$23^oC \pm 0.7$	$29^oC \pm 0.8$
rh	50% ± 4.68	64% ± 10	49% ± 7
Pa	1050	2000	2050

Subject data recording systems

To assess the subjects response to the environment, subjective data was collected from each subject prior to entering the chamber, on entry to the chamber and every fifteen minutes thereafter. The scales used were:

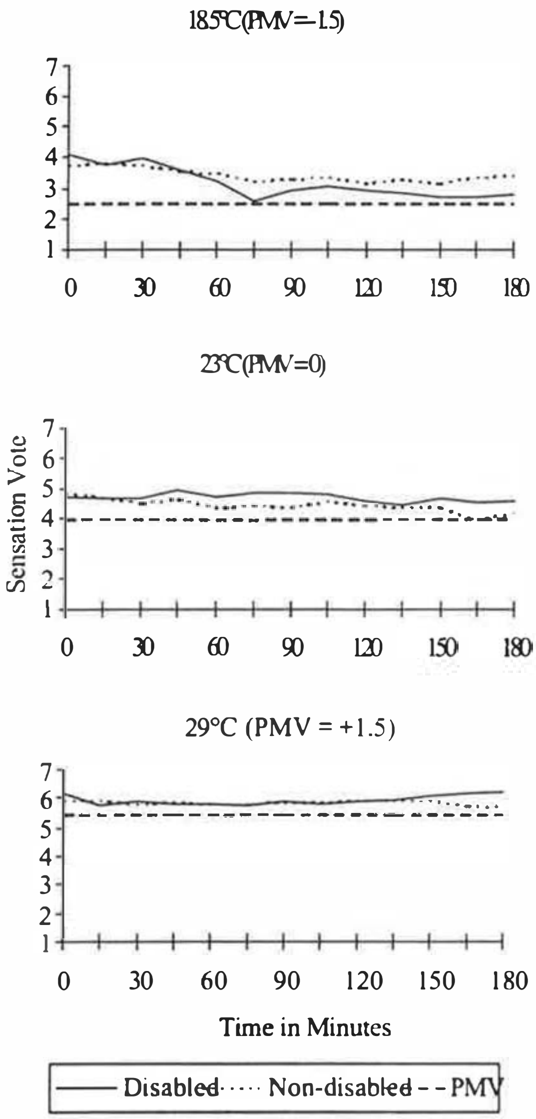
- The 7-point ASHRAE Scale from cold to hot (Parsons 1993).
- A 3-point preference scale, warmer, no change and cooler.
- 4 point scales for expression of how Uncomfortable, Dry, Sticky and Draughty they were.
- In addition subjects were asked to state the main area of discomfort in the body, and whether they were satisfied with the environment at present and how acceptable they would find it everyday.

Results

Population results - people with, compared to people without, physical disabilities. thermal sensation

Taking into consideration the thermal sensation vote, over the last three scores of the three hour experimental session, the mean comparison showed that there was little difference between the two population groups. See Figure 1 for Overall Body - Mean Thermal Sensation. The spread and range of votes within each group shows that people with physical disabilities gave a greater variation in their responses and were less in agreement with each others votes compared with those of people without physical disabilities at 18.5^oC, PMV = -1.5, slightly cool to cool and 23^oC, PMV = 0, neutral. The situation is reversed at 29^{o}C, PMV = +1.5, slightly warm to warm, where people without physical disabilities showed a wider ranging response see Figure 2.

Overall Body - Mean Thermal Sensation by Population



Range of Mean Thermal Sensation by Population

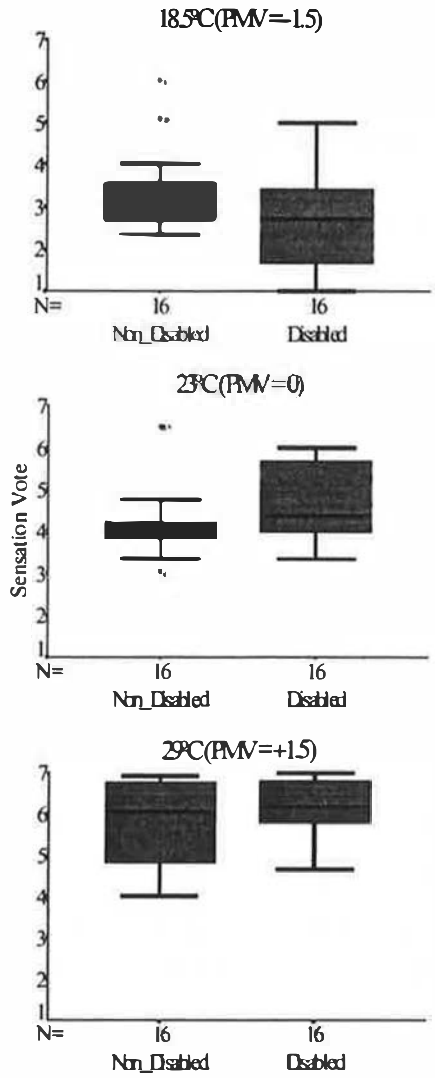


Figure 1 Shows The Actual Mean Vote (AMV) of Overall Thermal Sensation for People with Physical Disabilities Compared with those of People without Physical Disabilities and the PMV for the Three Experimental Conditions.

Figure 2 Shows The Range of the Actual Mean Vote(AMV) of Overall Thermal Sensation for People with Physical Disabilities Compared with those of People without Physical Disabilities.

(The Shaded boxes shows 50% of responses, T bars are the ranges, solid line is the median. with o * being outliers)

Note: For both figures above, Sensation vote/ASHRAE scale: 1=cold, 2=cool, 3=slightly cool, 4=neutral, 5=slightly warm, 6=warm, 7=hot. PMV Scale ranges from -3 cold to +3 hot, for purposes of presentation the ASHRAE scale is used. e.g. PMV = +1.5 = 5.5 on graph.

Percentage dissatisfied

There was no significant difference (p>0.05) between the population groups for the percentage of people dissatisfied with their thermal environment under the three conditions. The percentage dissatisfied was slightly higher than that predicted by Fanger (1970) See Figure 3.

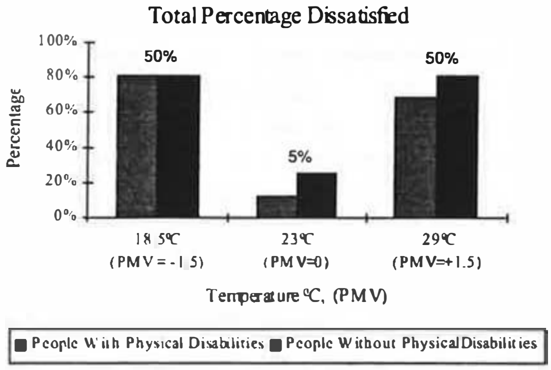


Figure 3 Shows the percentage of people dissatisfied for people with physical disabilities compared with those of people without physical disabilities for the three experimental conditions of PMV +1.5, 0 ,-1.5. The percentage figure labels show Fanger's (1970) Predicted Percentage Dissatisfied for those conditions.

Interaction between population and gender.

An analysis of variance test showed that there was no significant effect of gender and no significant interaction (p>0.05) between population and gender groups. See Table 2.

Table 2. Significance scores for interaction between population and gender for the three environmental conditions of PMV = -1.5, 0, +1.5

Environment ºC	PMV	Significance of F.
18.5ºC	PMV = -1.5	p = 0.260
23ºC	PMV = 0	p = 0.865
29ºC	PMV = +1.5	p = 0.537

Subjects with disabilities

Subjects with disabilities showed a wide range of responses to the same environment. Below are provided examples of subjects, their disability and their identified thermal requirements:

Subject 1 - Diabetic, Heart Condition, Kidney Transplant, Visually Impaired, Asthma -This subject would prefer a neutral to cool environment, 18.5^{O}C, PMV = -1.5, slightly cool to cool and 23^{O}C, PMV = 0, neutral.

Subject 2 - Two Strokes and Brain Surgery twice -Subject 2 was satisfied at the 23^{O}C, PMV = 0, neutral environment. Overall her responses were as expected by the predicted mean vote.

Subject 3 - Encephalitis -This subject preferred to be 'warm' however this occurred most consistently at the predicted mean vote of 'neutral'. This subjects suffered local sensation issues at the below knee and feet. This subject needs to feel warm to be satisfied, but this can be achieved at 23^{O}C, PMV = 0, neutral or at times during 29^{O}C, PMV = +1.5, slightly warm to warm. This subjects responses do not match that of the predicted mean vote.

Subject 4 - Left side weakness, wheelchair user, blackouts, due to road traffic accident 1994, Asthma - Subject 4's requirements were best provided for in the 23^{o}C, PMV = 0, neutral condition, though she had local requirements below knee and feet. This subject was 'very uncomfortable' experiencing a wider range of responses to the 18.5^{o}C, PMV = -1.5, slightly cool to cool condition.

Discussion

No significant differences were found between people with physical disabilities and people without physical disabilities. The people with physical disabilities were a heterogeneous group. The wide ranging responses suggests that this group can not be grouped together. It suggests that either individual responses or some means of classifying this population may be of greater value in the attempt to identify whether or not people with physical disabilities or subgroups of this population have different thermal comfort needs. The present study does not show any such differences and it is possible that individuals extremes of responses are cancelling each other out to provide a mean that is the same as that of the people without physical disabilities.

The above statement applies for the conditions which are required for PMV's of -1.5 and 0. The results for PMV= +1.5 seem to present some other phenomena that is occurring where people without physical disabilities showed a wide ranging response. People with physical disabilities on the whole showed a consensus in their response to this environment.

Votes on the sensation scales were matched well with subjects responses on the preference scales. This suggests that the thermal comfort model of PMV is applicable to people with physical disabilities as their preferred thermal environment responses match that expected from their actual thermal environmental responses.

The results suggests that people with physical disabilities have greater variation in their needs at 18.5^{o}C and 23^{o}C PMV -1.5 and 0 whereas at 29 ^{o}C PMV = +1.5 they are much more likely to have a similar response to each other.

Conclusions

When looking at the population and gender groups as whole groups the following conclusions can be drawn.

There were no significant differences found in the Thermal Comfort requirements of people with physical disabilities and people without physical disabilities.

Results showed that subjects responded as predicted by Fanger's thermal comfort model, with regards to the predicted mean vote. However, the predicted percentage dissatisfied was higher in our subject groups than Fanger's PPD would have expected.

This study therefore suggests that the thermal comfort model of predicted mean vote (PMV) can be used to predict comfort conditions for people with and without physical disabilities. The predicted percentage dissatisfied (PPD) however underestimated the PPD of the sample group.

Having concluded the above it is necessary to consider the wide range of responses that were given by people with physical disabilities at PMV = -1.5 and 0. It is therefore suggested that further research is required to identify means of classification of people with physical disabilities in relation to their thermal comfort requirements.

Bibliography

Breslin R, (1995) Gender Differences and Thermal Comfort Requirements. BSc Final Year Project, Loughborough University, Loughborough. (Unpublished)

BS EN ISO 7730 (1995) Moderate Thermal Environments - Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort, British Standards Institute, London.

Fanger PO (1970) Thermal Comfort, 1st edn. McGraw-Hill Book Co, New York

Giorgi G, Megri AC, Donnini G, Haghighat F (1996) ASHRAE Research Project 885-RP. Responses of Disabled Persons to Thermal Environments. ADN Inc, Montreal Canada

ISO 7730 (1994) Moderate Thermal Environments - Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort, 2nd edn. International Standards Organisation, Geneva, ref no ISO 7730:1994(E)

Parsons KC, (1993) Human Thermal Environments, Taylor & Francis, London

Yoshida JA, Sugiyama T, Matsui H, Haibara S, Kakudate M, Iwabuchi K, Imai H (1989) A study on Thermal Environment Indicies Considering Physically Handicapped Persons.

Yoshida JA, Banhidi L, Polinszky T, Kintses G, Hachisu H, Imai H, Sato K, Nonaka M (1993) A Study on Thermal Environment for Physically Hanicapped Persons. Results from Japanese-Hungarian Joint Experiment in 1990. Journal of Thermal Biology 18:363-375

Yoshino H, Momiyama M, Sato T, Sasaki K (1993) Relationship Between Cerebrovascular Disease and Indoor Thermal Environment in Two Selected Towns in Miyagi Prefecture, Japan. Journal of Thermal Biology 18:481-486

Appendix

Thermal Comfort Subjective Scale

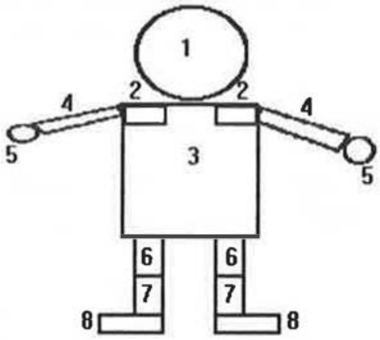
Session Number: .E/3/H............Subject No... E/MD/GH...

Name: ....

Session Start time.....................................

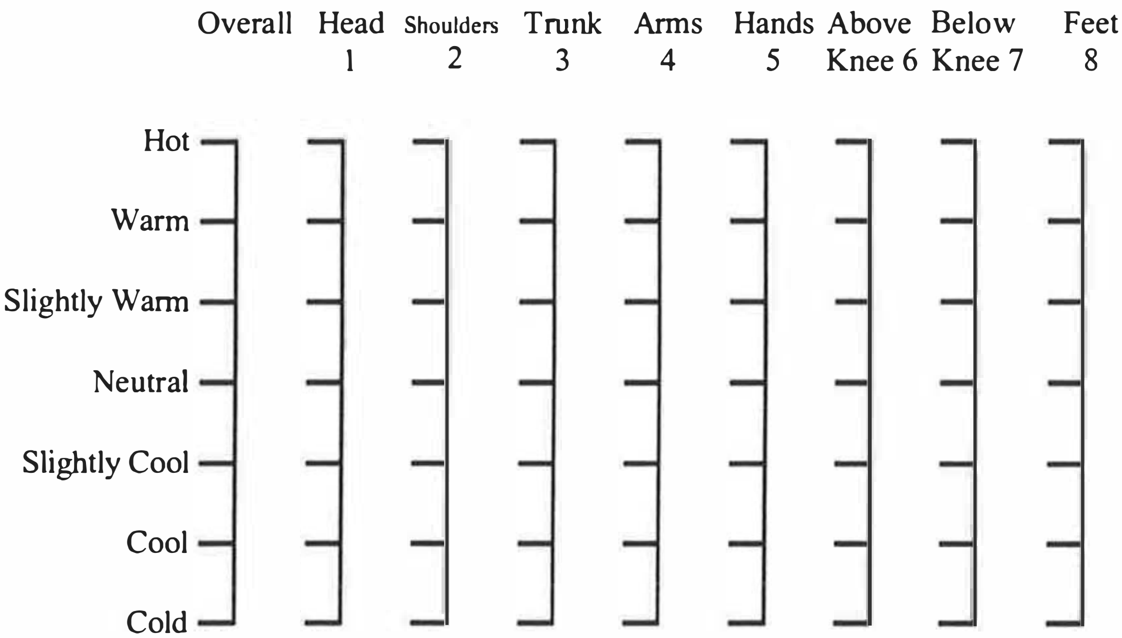
Time of completion.

	before	0	
15	30	45	60
75	90	105	120
135	150	165	180



Please answer the following questions concerned with YOUR THERMAL COMFORT.

1. With reference to the above diagram please indicate on the scales below how YOU feel NOW.



2. Please indicate how YOU would **like to be** NOW.

Warmer   No Change   Cooler

3. Please indicate on the following scales how YOU feel NOW.

Very Uncomfortable	Very Dry	Very Sticky	Very Draughty
Uncomfortable	Dry	Sticky	Draughty
Slightly Uncomfortable	Slightly Dry	Slightly Sticky	Slightly Draughty
Not Uncomfortable	Not Dry	Not Sticky	Not Draughty

Please state the main area of discomfort in YOUR body. ....

Please Tick ✓

4. Are you satisfied with your thermal environment NOW? Yes ☐ No ☐

5. Would you find this an acceptable environment to be in everyday Yes ☐ No ☐

6. Please give any additional information or comments which you think are relevant to the assessment of your thermal environment now for example, draughts, dryness, clothing, etc.

Now please hand this form to your experimenter

Thank you.

Photovoltaic roof tiles : design and integration in buildings

A. S. Bahaj & P.A.B.James, University of Southampton[1]

Abstract

The integration of photovoltaics (PV) into building facades and roof structures can provide a significant contribution to electricity generation. A design for a PV roof tile is proposed which will enable seamless integration with standard tiles in a roof structure. The constraints imposed by this requirement are discussed along with aesthetic, commercial and regulatory issues.

Introduction

Building integrated photovoltaics has a vast potential market in developed countries. Both commercial and residential buildings have large surface areas which are available for PV integration. In urban areas where land space is at a premium, the harnessing of such large areas is especially attractive. Roofs in particular provide an ideal site for photovoltaic electrical power generation. In general they represent large, flat surfaces which are less prone to shading than walls and exhibit more favourable inclinations for solar gain. A typical U.K. roof for example is pitched between 17.5 and 44 degrees. For optimum recovery, solar panels should be inclined perpendicular to the sun's rays. Clearly, a fixed solar array, such as a roof mounted structure cannot satisfy this criteria and so a tilt angle of near 45 degrees is likely to represent a good compromise.

Several options are available to achieve the integration of PV into roofs. In its simplest form, standard size modules can be mounted, i.e. "bolted on", to the top of the present roof structure. This crude approach does not truly integrate the PV with the building and produces the aesthetically poor result of a high value product being merely "tacked on" to the current structure. Moreover, it is widely recognised that it is important to offset the costs of PV installations by utilising modules not only for electrical generation but also for building cladding / roofing and as an architectural device.

As a first step to achieving this goal PV roofs have been installed using standard modules which are laid side by side across a roof deck. A capping is placed between the modules to ensure a watertight seal. This process however, requires a complex aluminum framing structure to be mounted onto a precisely formed predeck. The savings which result from the dual use of the photovoltaics are negated by the high cost of the framing and mounting structure. Although the finished roof, represents a major advance aesthetically over earlier bolt on solutions, the stepped effect obtained with traditional roofs, made of tiles is lost. The large size of the modules used (upwards of 50 x 100 cm) accentuates the inaccuracies that are present in the rafter and batten layout of a household roof structure forcing the production of the highly ordered predeck. The battens used for standard tiling could be applied to PV integration if smaller modules were used. A progression would be the production of a photovoltaic roof tile, which would be analogous with standard tiles.

In order to develop a photovoltaic roof tile it is first necessary to understand current roofing practice and materials. In the U.K., roof tiles form the primary barrier to the elements. The tiles are laid on wooden battens which run along the roof and are attached by special clips or nails. The battens are in turn nailed onto the rafters of the roof structure. A secondary level of protection is provided by a sarking felt which is laid between the rafters and the battens. This material provides insulation, prevents dust and air entering the roofspace and provides an extra waterproof barrier. A cut through image of a standard roof is shown (Fig. 1).The degree to which rows of tiles must overlap is defined by U.K.

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building regulations (minimum of 75 mm). The exposed length and width of the tile are known as the gauge and cover width respectively. In the U.K. there are two main manufacturers of roof tiles, namely Redland and Marley who produce not only a diverse range of tile sizes but also of styles (Fig. 2). Several tiles have raised edges (Redland Delta and Renown) or are curved (Redland Regent and Grovebury) and so are not suitable for PV integration due to the associated shading and the planar nature of current photovoltaic cells.

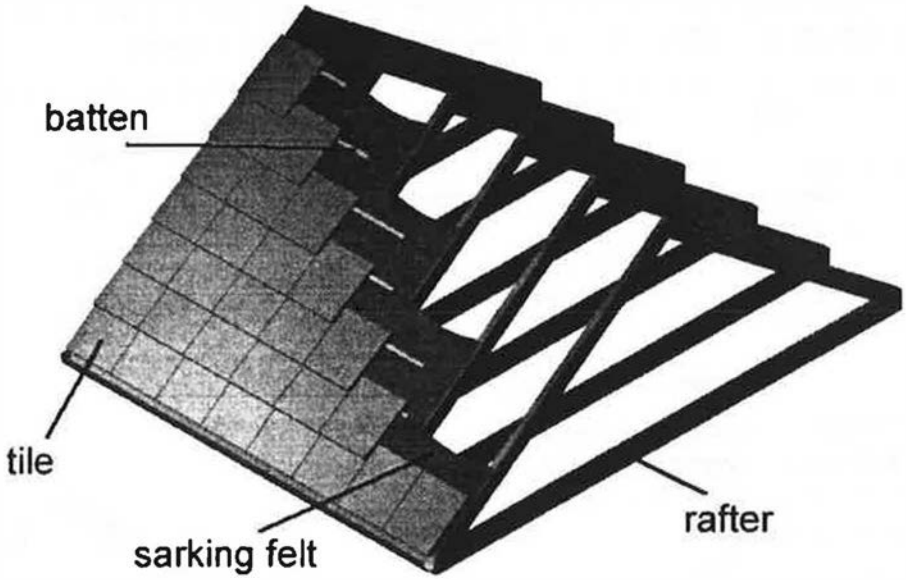


Figure 1: Section of a standard UK roof

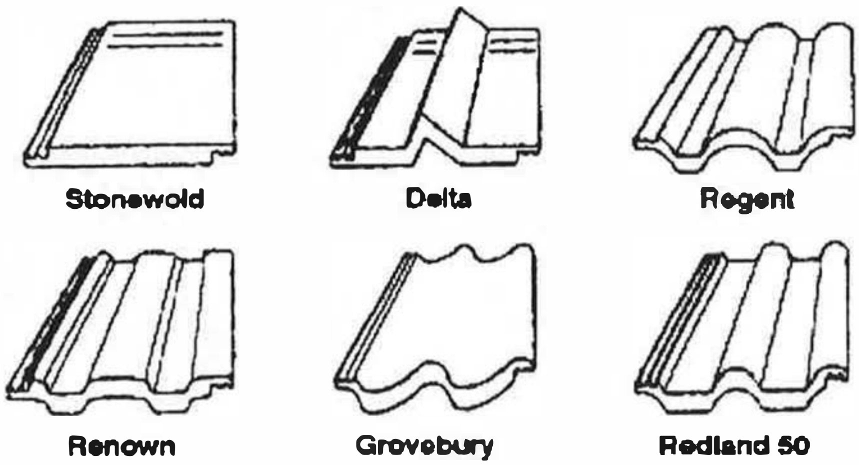


Figure 2: A selection of tile styles

In addition to the variability in tile size and style, the type of interlock used between tiles is tile specific. Clearly, to design a tile which satisfies the requirement of matching all types is an impossible task. The design of a variety of interlock connectors which could be mounted onto a template PV tile to produce the required shape is a possible solution [1]. However, the authors believe that this approach would raise the cost of the PV tile to a prohibitive level. Manufacturing a variety of linkages is detrimental to economies of scale and such a design will lengthen installation times. A typical domestic roof is 6 m deep and 8 m across. Approximately 500 standard tiles would be needed to cover this area at a tile cost of about £250-00 (tiles excluding clips ~ 47 p each). If a photovoltaic roof tile is designed around a specific standard tile, the majority of retrofit applications will require the current roof tiles to be discarded. The cost of discarding unsuitable tiles will represent a small fraction of the overall system cost and so will not effect the commercial viability of retrofit applications for PV tiles.

PV roof tile design

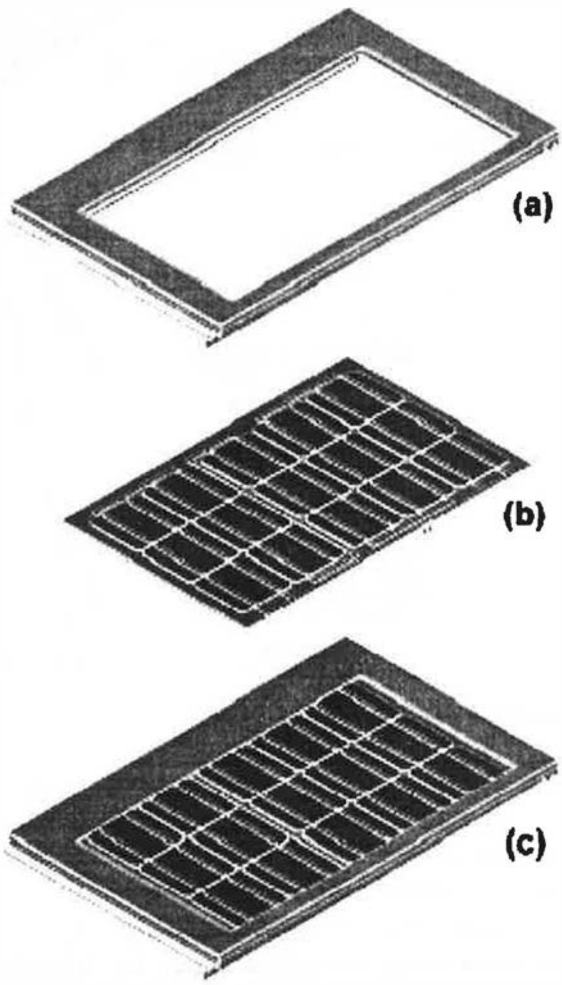
Accepting the prerequisite of a planar tile for integration yields a variety of suitable tiles for the design of an analogous PV tile. The PV tile must have the same depth and interlock as its standard counterpart but may have a cover width that is an integer multiple of the standard tile (e.g. 2x, 3x, 4x). Table 1 lists a range of suitable tiles and the resulting potential dimensions for a PV roof tile.

Company	Tile	Dimensions (mm)	Gauge range (mm)	Cover width (mm)	2X cover (mm)	3X cover (mm)
Redland	**Stonewold II**	**430x380**	**305-355**	343	**686**	1029
	Mini Stonewold	418x334	293-343	294	588	882
Marley	Modern	420x330	345 (max)	289	578	867
	Monarch	325x330	250 (max)	300	600	900

Table 1. Suitable roof tiles for PV integration

A standard roof has a lifetime in excess of 25 years. To successfully promote a photovoltaic roof a comparable lifespan must be offered. At present, photovoltaic technology is available in three distinct types, thin film, amorphous and monocrystalline. Monocrystalline technology is well established and module lifetimes of 20 years plus can confidently be expected. Both amorphous and thin film technologies are the subject of intensive research and potentially will provide significantly cheaper cells and modules. However, both technologies suffer from performance degradation with use and lifetimes of only a few years can be guaranteed. Monocrystalline therefore, represents the current technology that a PV tile must embrace to produce the required product. The dimensions of monocrystalline cells produced by all manufacturers are virtually identical being 100 - 104 mm square. An optimum size array of these cells must be fitted into the exposed surface of the PV tile.

Table 1 shows that a Redland Stonewold II tile for example, of double the normal cover width provides an exposed area of 355 mm by 686 mm. A 5 by 3 array of PV cells occupies an area of 379 mm by 579 mm which neatly fits into the exposed area, whilst retaining a sufficiently large surround for structural integrity. The proposed design is for a laminate to be formed of the 5 by 3 array of cells which is then inserted into the plastic tile surround from behind. The surround (a) and the PV laminate (b) for a PV tile (c) based around a Redland Stonewold II tile (2x cover width) is shown in Fig. 3.



(a)

(b)

(c)

Figure 3: PV cells integrated into a tile

The plastic laminate which holds the PV cells produces a robust surround which protects the cells from damage. This contrasts with traditional glass sandwich type PV modules which are very fragile and need careful handling.

Installation

Approximately 15% of the energy adsorbed by a monocrystalline PV cell is converted to electrical energy. The majority of the absorbed sunlight is dissipated as heat. The efficient dissipation of this heat represents a particular problem for roof integration. The sarking felt which sits on the rafters is generally a bitumen based material which softens at about 80 °C. Studies have shown that in a standard roof covered with ordinary PV modules temperatures can approach this level [2, 3]. The efficiency of PV cells is temperature dependant, with a rise in temperature having a corresponding reduction in cell efficiency. Therefore, control of the temperature of a PV roof is necessary in order to maintain both satisfactory array performance and sarking felt integrity. To provide sufficient ventilation it is necessary to increase the distance between the sarking felt and the rear of the PV tiles. A spacer must be placed behind the battens to increase the tile - felt gap to approximately 10 cm. A convection process can therefore, be established allowing air to enter through holes in the soffit and exit at the top of the roof. An added benefit of PV tiles in this respect is that standard tiles specifically designed for ventilation purposes can be used.

A typical photovoltaic household application is for a 3 kW system. Currently, standard PV modules cost about $4.5/W (£3/W) although prices are continually falling. The cost of the photovoltaic material, for a standard, module based system is nearly £10,000. In addition to this, metering, installation, cabling and an inverter to convert the produced DC power to domestic rating AC is required. The total cost of a system is approximately £15,000-20,000.

The payback times for PV systems in pure economic terms are very long at present. To maximise the benefit of a PV system it is important that the user makes use of the 25 year working life. Modern life however, is increasingly transient in nature, with the "job for life" expectations of previous generations no longer holding true. Short term employment contracts lead to the frequent need to move in order to find work. Traditional PV installations cannot easily be moved to another house as they are generally a custom design for a specific building. It is highly unlikely that on the sale of a house anywhere near the £15-20 K investment would be recovered. A PV system based on PV roof tiles offers a distinct advantage in this respect. The tiles can simply be removed from the roof and replaced with the analogous standard roof tiles with relative ease. The PV tiles can then be transported to the new house for re-use. The universal application of PV tiles will also generate a market for "secondhand" tiles.

Conclusions

Continual improvements in cell efficiencies coupled with reductions in production costs through new processes and economies of scale will enable PV to become an economic reality for urban power generation in the near future. Photovoltaic roof tiles have the potential to bring PV to the largest U.K. market, namely the home. A design such as that described in this paper, will enable PV to be integrated in an aesthetically pleasing manner. This is crucial to the success of the product in a market where consumers demand "green" energy alternatives but are reluctant to compromise their surrounding environment as a result. In addition, unlike other forms of PV installation, specialist contractors will not be needed for PV roof tile installations. A skilled roofing "trade" is readily available and would need no extra training to commission PV tile roofs In essence, the PV roof tile represents the combination of a mature tile industry, with state of the art plastic and photovoltaic technologies. In this way, a new approach to the integration of photovoltaics in buildings can be realised.

References

[1] Bahaj A.S. & Ward S.C., *The SOLATILE : A fully adjustable and Integrated Photovoltaic Roof tile*, Proceedings of 12th European Photovoltaic Solar Energy Conference, pp 1097-1100, 1994.

[2] Yang H.X., Marshall R.H. & Brinkworth B.J., *An experimental study of the Thermal Regulation of a PV-Clad Building Roof*, Proceedings of 12th European Photovoltaic Solar Energy Conference, pp 1115-1118, 1994.

[3] Okuda N., Yagiura T., Morizane M., Ohnishi M. & Nakano S., *A new type of Photovoltaic Shingle*, Proceedings of the IEEE First World Conference on Photovoltaic Energy Conversion, pp 1008-1011, 1994.

Prediction of energy use in food retail stores using artificial neural networks

S. A. Tassou and D. Datta, Brunel University[1]

Summary

The work presented in this paper reports preliminary results on a project funded by the EPSRC. The project which started in August 1996 aims to investigate the application of Artificial Neural Networks (ANNs) for the prediction and control of electrical energy consumption in retail food stores. Early results indicate that the most important independent variables determining the accuracy of prediction are the day of the week and time of day with indoor and outdoor environmental conditions being much less significant. The simple Networks investigated so far provide fairly accurate overall load prediction but fail to determine accurately the sudden change in load that takes place on store opening and closing. To address this problem the networks will be refined to include some known store operating characteristics such as time of opening and shut-down on weekdays and weekends and operating schedules of bakery, dry cleaners etc. From the present work and the work of other investigators in related fields it can be concluded that ANNs can become a valuable tool in the prediction of load demand and energy consumption in retail food stores, commercial buildings and other process systems. ANNs can also be used for on-line performance analysis and system diagnostics to identify malfunctions in equipment, maintenance requirements etc. Simple ANNs can be implemented on existing computer based monitoring and control systems at very little extra cost.

Introduction

Retail food stores are amongst the greatest single end users of electricity with refrigeration systems accounting for more than 50% of the electricity used. Lighting accounts for about 25% with the HVAC equipment and other utilities accounting for the remainder.

Energy consumption can be minimised only through better understanding of the consumption patterns and better control of the major energy consuming equipment in response to external environmental conditions and occupancy levels. The recent introduction of computer based monitoring and control systems provides the opportunity not only to characterise the various energy consuming processes in the store but to relate consumption patterns to fuel pricing and tariff structures and to develop advanced control techniques to minimise electrical maximum demand, energy consumption and fuel costs. It may be possible to perform these tasks on-line by employing adaptive control through predictive neural networks (ANNs).

Artificial neural networks are an attempt to recreate simple biological networks by joining together `cells' or `nodes' in a cascaded fashion. When a given set of cells (the inputs) are stimulated, the signals are passed through the network from node to node and finally exit the network through another set of simplified nodes (the outputs). Any given node accepts input from a number of other nodes, then outputs a signal based on the sum of all the inputs. Each node is connected to other nodes through a series of weighing factors by which its output signals can be simplified or attenuated. The trick to `training' a network is to find weights such that a given set of inputs causes the network to yield the desired output. One such learning algorithm is called back-propagation, whereby the weights are adjusted to reduce the error between the actual and desired outputs of the network. Detailed descriptions of different network configurations and training techniques are given by Rumelhart and McClelland [1] among many others.

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Neural networks behave very much like non-linear regressions with their ability to associate specific input and output patterns. One facet of neural networks, however, is that a statistical understanding of the relationships between the independent and the dependent variables is not needed. However, as with any modelling method, improved performance for a network can be expected when well chosen independent variables are used. Continuous analysis of the independent variables can lead to well chosen network inputs.

Artificial neural networks have been applied successfully to a number of engineering problems and research has shown that they may be more reliable building energy predictors than traditional simulation models [2,3,4].

This paper reports preliminary results of a project funded by the EPSRC and supported by Safeway Stores PLC and Elm Ltd on the application of ANNs for the prediction of energy use in retail food stores. The aim of the project, which started in August 1996, is to first develop an efficient energy predictor from half-hourly data and then extend the system to perform data screening, diagnostics, and optimisation of energy use.

Experimental set-up and monitoring

The investigations are based on a Safeway retail food store situated in Airdrie. This store is equipped with an Elm central monitoring and control system which monitors the temperatures in the display cases in the store and controls the refrigeration packs. For the purposes of the project the system has been extended to incorporate a number of additional measuring points which include:

- Temperature and relative humidity in the store
- External air temperature and humidity
- Solar irradiance
- Total electrical power consumption of the store
- Electrical power consumption of the refrigeration packs
- Gas consumption
- Underfloor heating flow and return temperatures
- Instantaneous store occupancy (shopping activity)

All the above data is logged every 15 minutes through a modem on a personal computer at Brunel University for analysis. Figure 1 shows a typical daily variation of the external and internal conditions and the total electrical load of the store. Although the temperature in the store is controlled by the heating and ventilating system the relative humidity is allowed to vary. As can be seen from Figure 1 this variation is fairly small. The external relative humidity during the winter months is high and remains fairly constant whereas the external temperature rises during the day and drops during the night in a sinusoidal fashion as expected.

From Figure 1 it can also be seen that during the night there is a base load on the store comprised mainly of the refrigeration load which includes the compressor packs, the condenser fans and the display case evaporator fans. On store opening in the morning the load increases sharply due to the store lights and other ancillary equipment being switched on and then drops again down to the base value on store closing in the evening.

Total electrical load prediction using neural networks

As mentioned earlier, a neural network is a non-linear mapping of the space between an input data set and an output data set and consists of three parts - an input vector (independent variables), an output vector (dependent variables), and an algorithm that maps the input space to the output space. One or more hidden layers connect the external layers by a set of "weights", expressed as two-dimensional matrices, W. In a feed-forward neural network, the value of each node in a particular hidden layer is the result of a non-linear transfer function whose argument is the weighted sum over all the nodes in the previous layer plus a constant bias B.

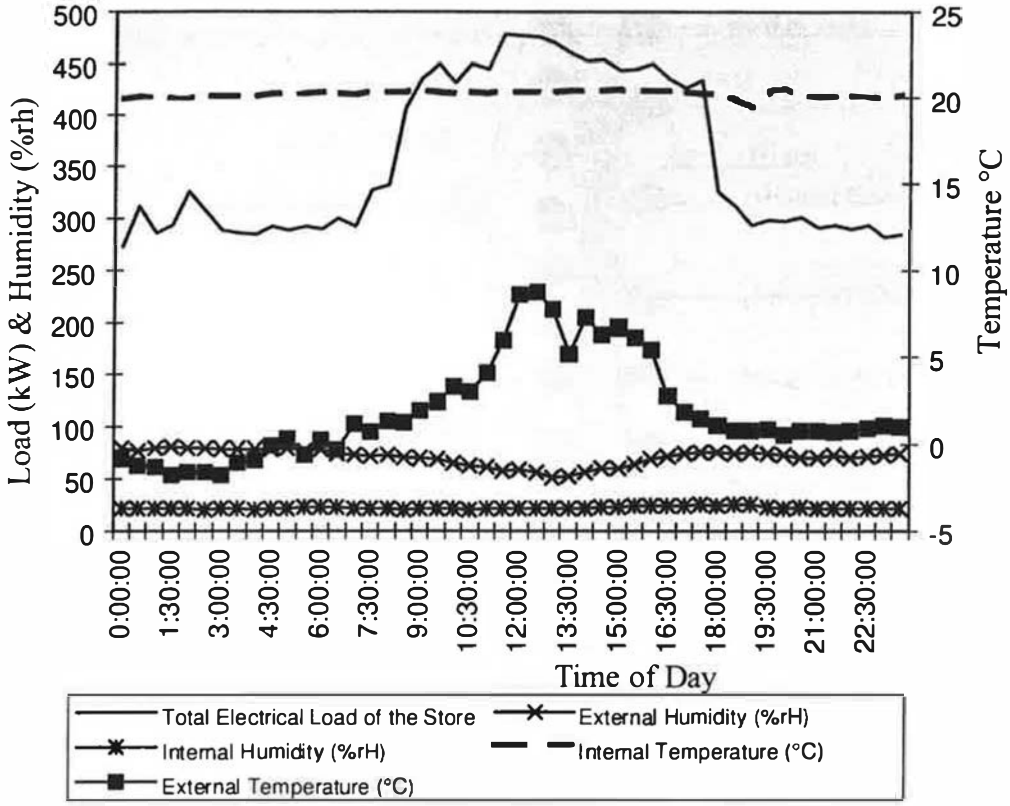

Figure 1. Total electrical load and indoor and outdoor environmental conditions over a 24 hour period

A variety of training algorithms are available but in general, to train a network, one begins with a set of training data consisting of the input vector, X_0^m and corresponding target vector, T_m. The internal weights are adjusted until the sum of differences between the neural net outputs Y_m and the corresponding target T_m is minimised to a predetermined level for all the training data.

A neural network with zero hidden layers is a linear expansion and a network with one hidden layer and a single output can be represented by[5]:

$$Y_m = \sum_{i=1}^{N_1} W_2(i) F \sum_{j=1}^{N_0} W_1(i.j) X_0^m(j) + B_1$$

In the above equation, N_1 is the number of nodes in the hidden layer and N_0 is the number of independent variables.

A sigmoidal function is usually used for the transfer function F as it enables a finite number of nodes in the single hidden layer to uniformly approximate any continuous function. Training of neural networks is frequently performed using a back-propagation algorithm. This algorithm iteratively adjusts the weights to reduce the error between the actual and desired outputs of the network. Simple three layered feed-forward neural networks were trained using the back-propagation algorithm and the actual measured data collected from the store. A schematic representation of a typical 3-layer network is shown in Figure 2.

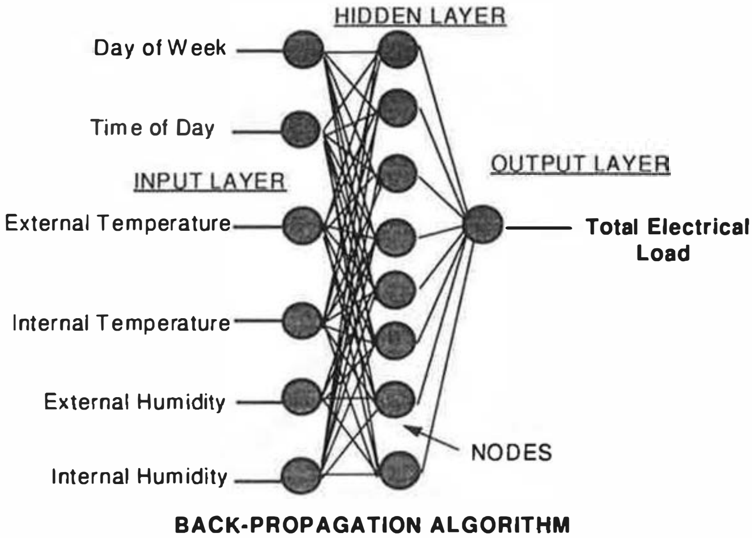

Figure 2. Schematic representation of a 3-layer network

The networks varied in terms of the number of input variables, i.e. input nodes, n. The number of nodes of the hidden layer varied as a function of the input nodes as (2n + 1). Both training and testing were carried out using a 32-bit commercially available neural network modelling package. The input variables (input nodes) used in each network configuration are listed in Table 1.

Table 1. Input Nodes used to train different Neural Networks

Network No.	Independent Variables
Network 1	Day, Time, External Humidity and Temperature for long term i.e. a 4 month with single hidden layer.
Network 2	Day, Time, External temperature for 4 months with single hidden layer.
Network 3	Day, Time, External Humidity for 4 months with single hidden layer.
Network 4	Day, Time, 4 months with single hidden layer.
Network 5	Time for 4 months with single hidden layer
Network 6	Day, Time, External Humidity and Temperature over 4 months with 2 hidden layers
Network 7	Day, Time, External Humidity and Temperature for short term i.e. month with single hidden layer
Network 8	Day, Time, Internal Humidity and Temperature and External Humidity and Temperature over one month with single hidden layer
Network 9	Day, Time and Internal Humidity over one month with single hidden layer
Network 10	Day, Time and Internal Temperature over one month with single hidden layer
Output Node	**Power in kW**

Prediction results using neural networks

Table 2 compares the performance parameters of the various networks during training and prediction testing.

Table 2. Summary of Network Performance

	Max. Error (kW)	Correlation	RMS Error
Training			
Network 1	118.6115	0.92415	0.075375
Network 2	131.5245	0.92754	0.073488
Network 3	149.1984	0.92122	0.076508
Network 4	150.002	0.9144	0.079937
Network 5	153.9148	0.90352	0.084656
Network 6	132.5156	0.92365	0.075523
Network 7	136.4494	0.91061	0.08475
Network 8	102.717	0.9524	0.066144
Network 9	117.8549	0.94138	0.073689
Network 10	107.6669	0.94529	0.070835
Testing			
Network 1	129.5148	0.92426	0.075278
Network 2	118.122	0.91673	0.079696
Network 3	149.4032	0.90879	0.083096
Network 4	126.3457	0.92897	0.072545
Network 5	132.8639	0.91452	0.80421
Network 6	122.6874	0.92589	0.074985
Network 7	94.44321	0.90485	0.08417
Network 8	117.3663	0.95429	0.069534
Network 9	66.50726	0.95092	0.068498
Network 10	63.25943	0.96375	0.060049

From the above table it can be seen that although all the networks show a fairly good correlation and low RMS error, the maximum error is quite high and in some networks exceptionally high. This is because the networks in their present simple form are unable to predict the load accurately at times where there are very sudden changes in load, for example during opening and closing of the supermarket where the lights are switched on and off respectively. Lighting represents a high percentage of the total electrical load in supermarkets, up to 30%. To address this problem in work to be carried out over the next few months the store's main operating characteristics such as opening and closing times will be incorporated in the networks.

Table 2 also shows that higher prediction accuracy is obtained when short-term training data (data from previous month) is used rather than long term data (data from the last 4 months) . This may be due to the fact that the effects of sudden changes in weather conditions and store operating patterns are lost when long term data are used for network training.

Figure 3 compares the prediction using Network1 with the actual data for 15 days in April 1996. The Network was trained using actual data from the 4 previous months, December 1995 - March 1996). It can be seen that the network traces the actual data quite well, apart from the fluctuations in the base load and maximum load and the rate of change of load on opening and closing of the store. This problem will be addressed by enhancing the networks through a) the introduction of some store operating characteristics such as opening and closing times in the networks , b) combining time series with independent variable modelling or c) a combination of (a) and (b). It has been found by other investigators[6] that combining time series with independent variable modelling improves the performance of the network in regions of random fluctuations of the dependent variable.

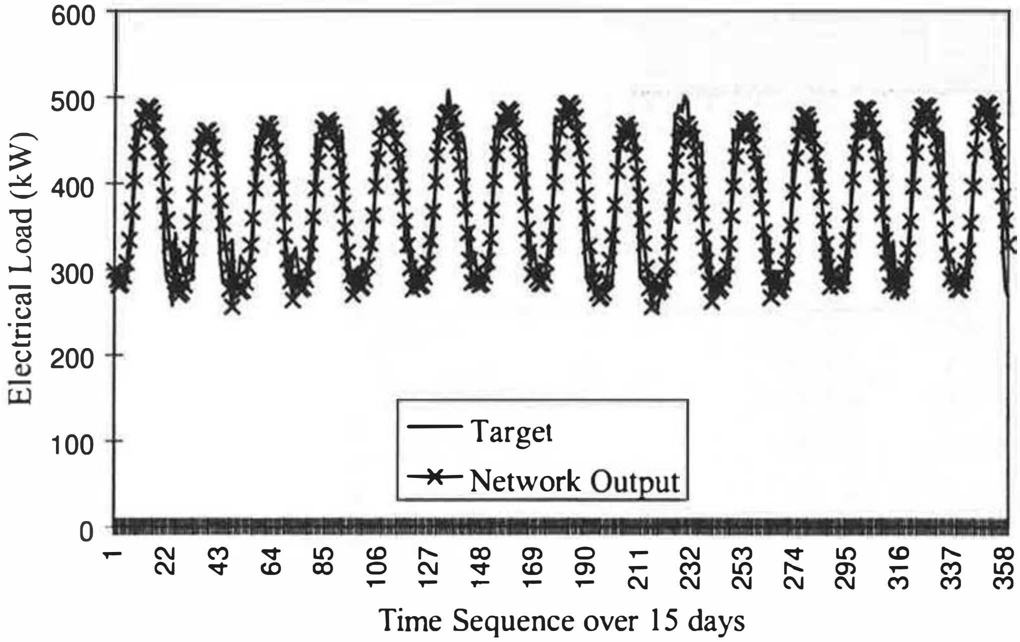

Figure 3. Comparison between predicted and actual data over a 15 day period

Table 3. Percentage contribution of the independent variables towards dependent variables

	Day	Time	Ext. Humidity	Ext Temp.	Int. Humidity	Int. Temp.
Network 1	10.53	66.667	3.859	20		
Network 2	10.53	69.47		21.053		
Network 3	13.04	83.48	4.35			
Network 4	13.04	86.96				
Network 5		100				
Network 6	10.53	67.37	2.1	20		
Network 8	7	36.5	10.5	7.3	11.2	27.5
Network 9	7.72	77.54			14.74	
Network 10	7.72	77.54			14.74	

Table 3 gives an indication of the percentage contribution of the various independent variables to the accuracy of prediction of the dependent variable. It can be seen that the time of day is the most significant independent variable with all other variables having a much lower effect. It should be stressed, however, that more detailed analysis is required to determine the relative importance of each variable and, hence, the instrumentation that would be required for on-line electrical power prediction. This area will be the subject of further investigations over the next few months.

Conclusions

1. The ANN approach is a generic technique for mapping the relationships between inputs and outputs and requires less expertise and experimentation than traditional modelling of non-linear multivariate systems.

2. Results in this paper show that a simple ANN architecture with one hidden layer can provide predictions of overall electrical energy consumption with a reasonable degree of accuracy. However, the simple networks used give rise to relatively high maximum errors in instantaneous load prediction during sudden changes in load. They also fail to predict random load fluctuations during steady state operation. These problems will be addressed in future investigations by introducing store operating characteristics in the network and perhaps combining time series with independent variable modelling.

3. To arrive at an optimal ANN architecture for on-line electrical load prediction, the contributing factors of the various input variables were analysed. The results showed the time of day to be the most important variable in all the cases with external and internal environmental conditions having a smaller effect.

4. Further work will involve development of ANNs to predict total as well as the load of various other energy consuming subsystems on-line to facilitate on line load management.

5 From the present work and the work of other investigators in related fields it can be concluded that ANNs can become a valuable tool in the prediction of load demand and energy consumption in retail food stores, commercial buildings and other process systems. ANNs can also be used for on-line performance analysis and system diagnostics to identify malfunctions in equipment, maintenance requirements etc. Simple ANNs can be implemented on existing computer based monitoring and control systems at very little extra cost.

Acknowledgements

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References

1. Rumelhart, D. E. and McClelland, J. L. (1986), "Parallel distributed processing explorations in the microstructure of cognition", Cambridge, MA; MIT Press.
2. Kreider, J. F. and Wang, X. A. (1991), "Artificial Neural Network demonstration for automated generation of energy use predictors for commercial buildings", ASHRAE Transactions, 97(2), pp. 775-779.
3. Anstett, M. and Kreider, J. F. (1992), "Application of Neural Networking Models to predict energy use", ASHRAE Transactions, Paper No. 3672, pp. 505-517.
4. Stevenson, W. J.(1994), "Using Artificial Neural Networks to predict building energy parameters", ASHRAE Transactions, 100(2), Paper No. OR-94-17-4.
5. Feuston, B. P. and Thurtell, J. H. (1994), "Generalised non-linear regression with ensemble of Neural Nets: The Great Energy Predictor Shootout", ASHRAE Transactions, 100(2), Paper No. OR-17-3.
6. Kawashima, M., Dorgan, C. E. and Mitchell, J. W. (1995), "Hourly thermal load prediction for the next 24 hours by ARIMA, EWMA, LR and an Artificial Neural Nework", ASHRAE Transactions 101(1), pp. 186-200.

Energy modelling of building estates

D.K.Alexander, P.J.Jones, S. Lannon, Welsh School of Architecture[1]

Introduction

In the drive to promote sustainable architecture and urban development, many researchers and developers are proposing Integrated Local Energy Sources (ILES) serving groups of buildings; estates. These energy systems often seek to combine renewable energy sources (wind or solar energy) with Combined Heat And Power (CHP) units, so as to reduce the estates reliance on large scale energy suppliers and also to reduce pollution through increased operating efficiency.

The correct design of such complex systems requires the matching of the energy requirements of the estate and the supply characteristics of the renewable sources. The realisation of such systems will require credible estimation of energy and monetary benefits. Simulation tools are required to aid both those tasks.

This paper outlines a new EPSRC funded project exploring the efficiency of differing simulation techniques for the detailed modelling of such systems.

Integrated Local Energy Sources

ILES systems often seek to maximise overall energy efficiency by utilising "free" energy sources (wind or wave power, active or passive solar) and heat that may otherwise be wasted from other processes within the site. Often they seek to combine many such sources. These systems generally serve large groups of buildings (for instance a housing estate, business park or hospital estate) often containing dissimilar building types.

The operating efficiencies, and therefore the running costs and pollution output of such systems are highly dependant on the loads presented to them by the estate they serve. The heat and electrical production must be well matched to the heat and electrical requirement, or load profile, of the estate.

In determining the operating characteristics of ILES and for determining accurate costs and penalties of ILES designs, the estate load profiles for all these buildings must be known or estimated and matched to the supply capabilities of the ILES.

This is not generally a simple problem; the energy production of a particular ILES approach may be site dependant (for instance in a wind energy or active solar based system), it may be plant specific (for instance the electric to heat output ratios of CHP systems), or both. Combinations of sub-systems may interact adversely (for instance the electric energy produced by PV systems may offset that required from a CHP system, but not alter the heat required, therefore producing less efficient operation).

The energy use of the buildings also will be site dependant, but more importantly, dependant on the actions and influences of the occupants. Variations of the energy demand across the numerous buildings in a group will influence the match of supply and demand.

The adverse reaction to the performance of badly matched systems can only detract from the uptake of such technology.

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Single building modelling

Traditional applications of detailed modelling methods, such as HTB2 or ESP, have focused on one building (figure 1). The data requirement and computational effort can be restrictive for even that scale of application; often even one part of a large building may be studied.

Estates and neighbourhoods

In clusters of buildings the variation of demand from building to building across the estate may be significant; some may be served adequately, others less so. It is well known that occupancy effects can alter the energy demand of otherwise similar buildings by a factor of 3 or more. With the increasing take up of other energy saving measures (for instance low energy lighting, occupant awareness, etc.) this can only increase the dependency on occupancy effects. The existing knowledge base of building operation may not be sufficiently reliable for accurate economic calculations.

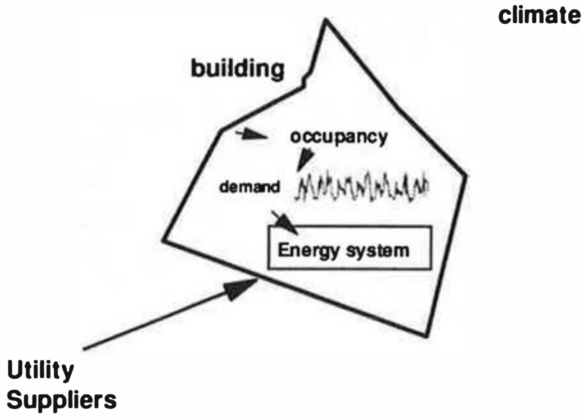

Figure 1 : Single building simulation

A building energy model may be used to predict both the energy demand profiles of individual buildings and the plant response to those demands. The effect of variations in occupancy (as in a housing estate), and building type (as in a hospital estate) across a group of buildings will not necessarily be linear. An analysis of an average building/occupant may therefore not be well suited to the task at hand, leading to badly matched systems.

We have then a requirement for a simulation method capable of dealing with multiple buildings, the operation of buildings (including occupancy effects), the energy requirements of buildings, the energy supply characteristics of ILES systems, and the interactions between all those components.

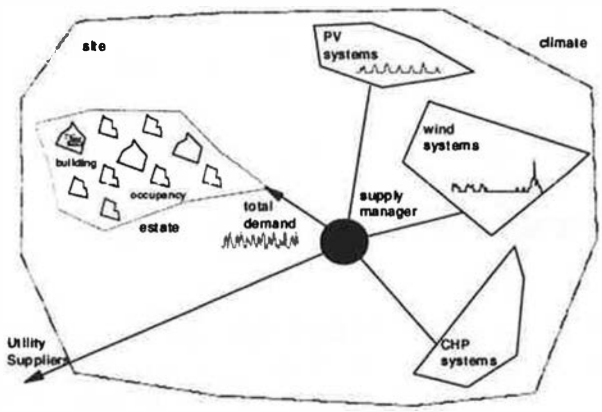

Figure 2 Estate and ILES simulation

Such a method could be achieved through one of two means; the explicit calculation of each building in the group, or the statistical manipulation of the characteristics of the group.

Explicit modelling

Groups of buildings could be simulated by simply expanding existing detailed modelling methods to allow sufficient zones and elements to describe the entire estate. The variations in the buildings across an estate is therefore handled explicitly.

The "scaling-up" of the detailed approach to encompass estates of buildings will be computationally inefficient; the explicit simulation one hundred buildings will take 100 times as long as one, and potentially produce 100 times the information. Simpler methods will be required in such an approach.

Yet there must be a limit to the extent of simplification. Detailed building models do contain information that is also often required by ILES models; solar geometry, site shading, wind effects, thermal loads and incidental energy requirements. These factors may be significant, for instance in the assessment of the utility of PV systems. Thus the advantages of such detailed modelling techniques must be kept whilst the disadvantages are circumvented.

Stochastic Modelling

Variations in occupancy may be best tackled by statistical techniques, allowing random variations in occupant influenced parameters, varying in effect as well as time. The example below illustrates the simulation of a 50 house estate, achieved through the simple statistical variation of a single example, figure 3. The match of the overall energy requirement to the predicted available energy from roof mounted PV and/or local wind turbine system is shown in figure 4. This example shows a small amount of surplus energy that could be provided to the grid system, but also shows a considerable reliance on grid power.

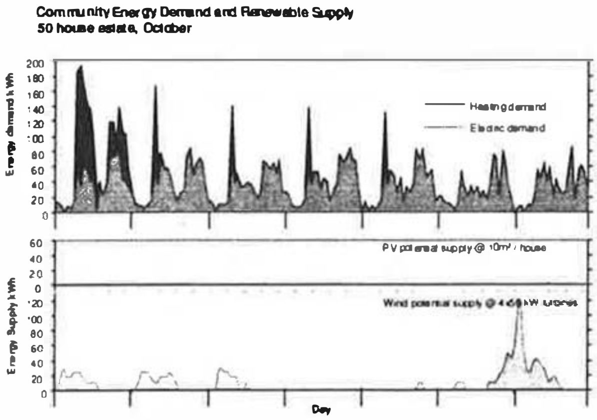

Figure 3 : Sample simulation of housing estate

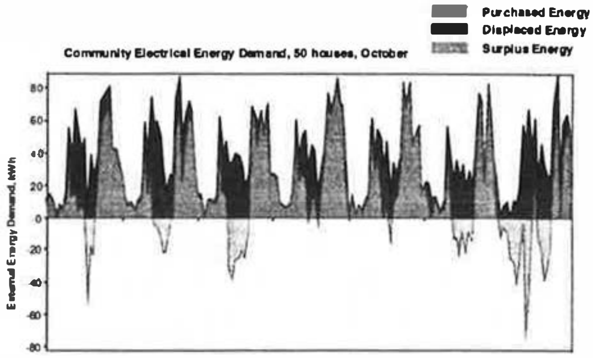

Figure 4 : Total energy supply and demand for sample simulation of housing estate

Unfortunately the statistical approach also expands calculation considerable as multiple simulations required for each case. Again alternatives to detailed simulations will be required, leading to the same background query; how far can simplification be driven without significant loss of the quality of the result?

Modelling limitations

The modelling techniques currently available for the simulation of building estates would appear to have 3 main drawbacks;

- the more sophisticated dynamic thermal models generally focus on one building. Scaling a single building to a larger estate may lead to errors, while an explicit simulation of all buildings in an estate would currently be time consuming.
- most thermal simulation techniques suppress natural occupancy variation in buildings; prescribed "average" occupancy patterns are generally used. Occupancy encompasses more than simply the times of robotic actions; the variations of energy use between similar buildings can only be ascribed to the behaviour and attitude of occupants, and their reactions to conditions (for instance in light or thermostat switching and window opening).

- plant and fabric option are often not well coupled within the same simulation model. Thus those models that simulate well, components of ILES systems may not have strong buildings models, and visa-versa. Ideally building and plant would be modelled to a similar strength within a common model.

Project objectives

This project will address these three issues, with the aim to produce a prototype simulation method for the energy modelling of groups of buildings served by ILES systems.

The specific objectives of the current project are:

(i) to investigate and assess the suitability of methods for the dynamic load simulation of groups of buildings. These will range from the explicit modelling of numbers of buildings (for instance in an enhanced version of HTB2), through the explicit modelling and scaling of representative buildings, the simplified modelling of numbers of buildings (for instance with a time-constant type thermal model), to the detailed stochastic modelling of buildings.

(ii) to review the current practice of modelling occupants and investigate techniques to account for occupancy effects. This may be through the explicit simulation of a number of differing occupants, through the simulation and scaling of an "average" occupant, through the stochastic modelling of a "variable" occupant, or through the development of a reactive occupant model.

(iii) to review available ILES component models and investigate their integration with building models, sharing common data for solar, wind, etc. resources.

The relative merits of the differing approaches will be assessed, primarily concentrating on the quality of data provided (e.g. the ability to correctly match the demand and supply of energy) and the computational efficiency of the approach (e.g. calculation time). It is expected that the explicit approach will provide the better solution in each case, but at the expense of computation time and complexity. The impact of the simpler approaches can be compared to this solution, in terms of the likely impact on the performance of target energy supply systems.

The successful identification of a efficient energy modelling approach for estates could provide the following benefits:

- it would allow more reliable and more efficient modelling of the built environment and energy sources for estate managers and designers.
- it would allow an assessment of a "best mix" of building types for efficient use of local energy resources.
- it would allow an assessment of site planning and orientation to promote most efficient use of passive solar features.
- it may be expandable beyond estates to communities, towns and cities. As such it would complement the current development of tools for sustainable cities, such as the Energy and Environmental Prediction (EEP) model.
- it may be exploitable through genetic modelling techniques to allow energy-driven design, optimisation and operation of estates.

Conclusion

The successful application of integrated local energy sources serving groups of buildings depends on the matching of demand and supply characteristics. Numerical simulation tools are required to aid this design task.

The simulation of groups of buildings presents challenges to the model constructor, not the least of which are the increasing importance of occupancy effects and of the increased need for computational efficiency.
A new project, funded under the EPSRC ROPA scheme, is exploring the efficiency of different simulation approaches to the detailed modelling of such systems.

The objectives of the project are:

- to investigate and assess the suitability of methods for the dynamic load simulation of groups of buildings,
- to review the current practice of, and to explore new methods, for modelling occupancy effects on the energy use of buildings, and
- to review available ILES component models and investigate their integration with building models, sharing common data for solar, wind, etc. resources.

The results of these investigations will be used to construct a prototype "hybrid" model for the dynamic simulation of building estates and integrated local energy systems. The advantages of such a model will be to:

- allow more reliable and more efficient modelling of the built environment and energy sources for estate managers and designers,
- allow an assessment of a "best mix" of building types for efficient use of local energy resources.

Acknowledgement

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Investigating the effects of wind on natural ventilation design of commercial buildings

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Introduction

There has been a growing interest by building designers and their clients in the design of commercial buildings that are naturally ventilated or have some form of 'hybrid' combined natural and mechanical ventilation system. Such buildings often incorporate innovative features such as chimneys, atria or roof wings, as part of the ventilation design. In many cases, natural ventilation systems are designed based on 'stack' performance, with the assumption that wind effects act to increase ventilation rates and thereby improve ventilation performance. This may indeed be the case for many designs, however, there will be cases when the wind effect will dominate and counteract the stack effect, which may cause air quality and thermal problems due to unintended internal air flow distribution

This project investigated, through simulation methods, the sensitivity of a number of natural ventilation designs to wind effects. Wind effects were found to significant, but in many cases, the design could be "tuned" to provide a more robust response to changing conditions. Design guidelines are presented.

Review of ventilation design

A review of design tools and of existing buildings that had either a natural or hybrid ventilation system indicated the following :

- A common thread of many designs was the apparent reliance on buoyancy (or 'stack') as the design case. Where wind was considered, the devices/strategies usually appeared to be unidirectional. The effect of the wind was generally assumed to be beneficial, that is, it could only improve the 'stack' ventilation performance.
- There are few design guidelines for 'wind' ventilation. Most design guidance again appears to concentrate on the buoyancy case, or often reinforces the concept of an invariant prevailing wind direction.
- The more advanced design methods that are capable of calculating the effects of wind driven ventilation, were generally found to be aimed at the engineering profession and are of limited applicability or interest to architects.

Generally, there is an indication that natural ventilation design is based on only a limited understanding of wind effects and their integration with stack effect, and that this may cause performance problems especially in the case of innovative design strategies.

Case studies

This project was carried out through case studies, subjecting or designs-in-development to analysis by two modelling methods; physical scale modelling using a wind tunnel and numerical simulation using computational fluid dynamics (CFD).

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Wind tunnel modelling

The WSA wind tunnel is an atmospheric boundary layer device, with a 2x2x1 m working area. Boundary layer wind profiles and turbulence levels were calibrated for urban, suburban and greenfield sites, for scales from 1:50 to 1:500.

CFD modelling

CFD simulations were carried out using FLOVENT and DFSAIR. FLOVENT is a commercial code aimed at the building design field and widely used in the building industry. DFSAIR is a code owned by the environmental consultants Design Flow Solutions, and is capable of detailed simulations through access to the source code

In this paper, two studies are summarised in detail, while the remaining four studies are only briefly described.

Case study : Saga Group HQ

The Saga Group Headquarters is a prestige commercial office building under design by Michael Hopkins and Partner (Fig 1). The natural ventilation strategy is intended to control the thermal conditions in the atrium space, in order to prevent summertime overheating. The office spaces are mechanically ventilated.

The designers' preferred solution was to have inlets and outlets on the front facade of the atrium at low and high locations respectively, leaving the top of the atrium structure free to be used as a terrace for the director's suite.

Wind pressure coefficients (Cp's) were measured in the wind tunnel at the proposed inlet and outlet positions (Fig 2). Initial testing of the design indicated that for the prevailing wind, while the terrace area would be located in a robust negative (suction) pressure region, relative to the bottom of the atrium facade (the proposed inlet area), the proposed vertically sloping outlet areas would have a relatively high positive pressure. This wind induced pressure difference would oppose the buoyancy pressures set up inside the atrium due to solar gains (Fig 3). This could lead to

- flow reversal at high wind speeds, a continuous air entry at the top of the atrium,

or, more importantly, to

- the wind and buoyancy forces balancing and negating each other. This would leave minimal ventilation caused only by wind turbulence.

The measurements suggested the latter would occur at moderate wind speeds (e.g. 3m/s).

A obvious solution to the problem would be to move the outlet to the horizontal terrace area, where there were strong negative pressures. However, this was not suitable for architectural reasons. Therefore, number of fixtures and devices were tested, to attempt to produce a relative negative pressure at the sloping vertical outlet.

The most promising of these was a 'wing' type of wind deflector which shielded the outlet from direct wind pressure, and promoted a smooth air flow past the outlet (Fig 4). Tests indicated that such a device would reduce positive pressures and increase suction pressure at the atrium outlets (Fig 5), so that wind and buoyancy forces worked together, through a wide range of wind directions.

The effectiveness of the device was sensitive and could be disrupted or negated by the addition of solid shading devices or balustrades on the terrace area, or by altering the size of the wing.

The alterations suggested through this work have been incorporated in the final design.

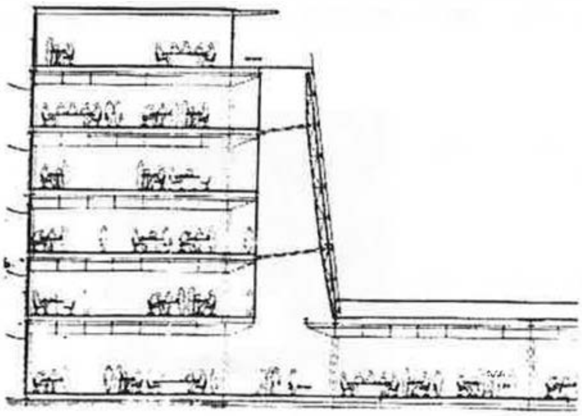


Figure 1. Initial design section showing the six levels of offices and atrium

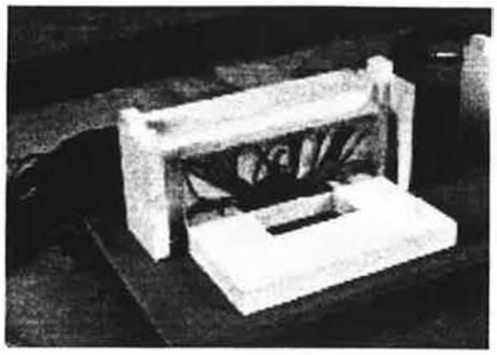


Figure 2. Wind tunnel model of design (1:200)

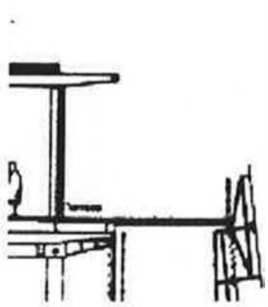


Figure 3 (left). Possible flow regimes under wind conditions

Figure 4 (right) Detail of suggested wind deflector

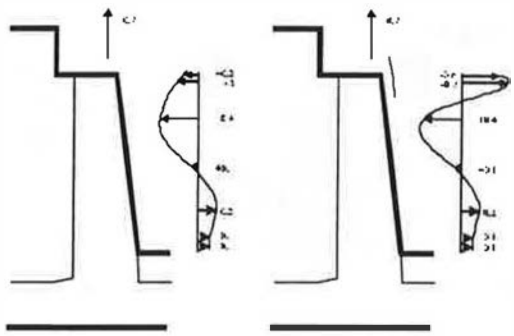


Figure 5. Wind Pressure variation along centreline of atrium, showing original and modified conditions. Note the creation of the large suction pressure due to the wind deflector

Case study: Balanced chimney

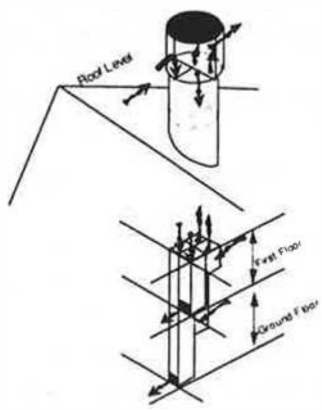


Figure 6 Schematic of the balanced chimney

This investigation studied the performance of a balanced inlet/outlet chimney device. The concept is based on the inlet facing the prevailing wind and the outlet in the wake, as indicated in Fig 6. An example of this system is the commercial 'Monodraught' device. Under stack-only conditions the room air will be exhausted at high level and supplied at low level.

Tests were carried out on a generic model to measure wind Cp's and allow flow visualisation at the chimney inlet and outlet locations for the following situations :

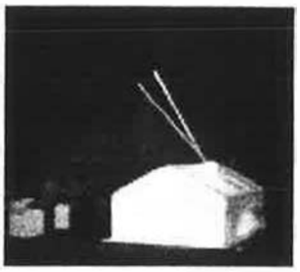
- varying wind direction,
- varying chimney locations and heights,
- varying proximity of neighbouring buildings.

Example results are presented as follows :

- Flow visualisation (Fig 7) and laser Doppler wind speed measurements (Fig 8). These allow a qualitative and quantitative investigation of the wind impact on the building and in particular around the chimney device.

Figure 7 (left): Smoke visualisation showing chimney in the wake of the ridge.

Figure 8 (right): Use of LDA probe to measure wind velocity and turbulence in the wake of ridge.



- Values of Cp for different chimney heights for a range of wind directions (Fig 9).
- A summary table of inlet/outlet Cp gradient (inlet minus outlet) values, for differing wind directions, chimney heights and proximity to other buildings (Table 1).

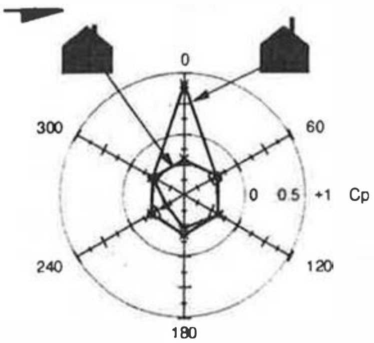


Figure 9 (left): Values of Cp for different chimney heights for the wind direction 'over the ridge'.

Table 1 (right): A summary table of (inlet minus outlet) Cp gradient

Case		
Isolated;		
Ridge level	+0.5	+0.0
Raised 1m	+0.6	+0.5
Large Building Nearby (1h);		
Ridge level	+0.2	+0.0
Raised 1m	+0.3	+0.5
Large Building Close (1/2h);		
Ridge level	+0.1	+0.0
Raised 1m	+0.2	+0.4

The tests showed the difficulty in providing a ventilation solution robust to wind direction. The balanced chimney device is sensitive to wind direction. To operate as a buoyancy device, a design decision must be made as to the location of room inlet and outlet positions (generally at low and high levels respectively). Under wind conditions, whilst there could always be a sufficient pressure to generate ventilation, some wind directions could cause the inlet to act as an outlet and visa-versa. Further, on duo-pitched roofs, the device was wind direction dependant, unless it was terminated at a considerable height (typically 1m) above the ridge. If sited at low level on a downwind side of the ridge, all positions around the device had similar mean pressures and so the wind induced ventilation would be minimal.

CFD simulations were carried out for the case of the chimney located on the ridge under summer conditions, for three situations, namely; (i) stack, (ii) 'wind (3m/s) enhancing stack', and (iii) 'wind opposing stack'. Figure 10 presents an example vector plot for the 'wind enhancing stack' case, indicating the room air supply and exhaust at low and high level respectively. Table 2 summarises the ventilation rates predicted for each case. The wind effect completely dominates stack effect, as indicated by the same ventilation rate for situation (ii) and (iii).

Case	Ventilation rate (ac/h)
stack (7°C)	1.7
'wind (3m/s) enhancing stack'	2.4'
wind (3m/s) opposing stack'	2.4

Table 2: Summary of ventilation rates from CFD simulations.

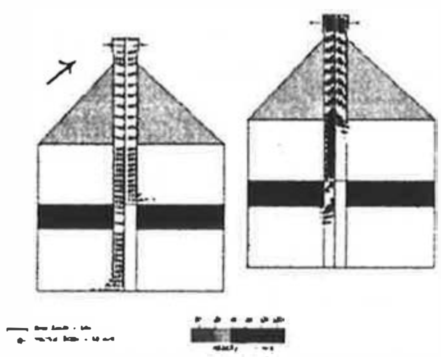


Figure 10: An example vector plot for the wind enhancing stack' case showing sections through the inlet and outlet stacks.

Case Study : Ventilation wing

This study was of a large exhibition hall (Fig 11), designed by Thomas Hertzog and Partner. It is a large low-lying building which utilises a repeated curved roofline with high level outlets located along the ridges, protected by 'wing' wind deflectors. Inlets are located around the walls. Tests indicated that although there were generally negative pressures at the ridge outlets; the wings did little to enhance ventilation due to the high levels of turbulence caused by the building form. The shape of the wings was adjusted to investigate the potential for enhancing the negative pressures at the outlets. However, only relatively minor improvements were indicated. The form and scale of the building overshadowed the effect of relatively small scale add-on outlet devices.

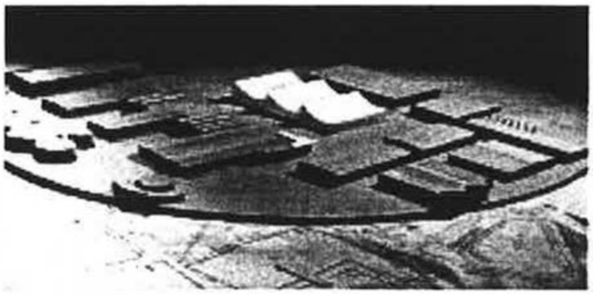


Figure 11 : Wind tunnel model of .proposed exhibition hall, showing extent of surroundings included in model.

Case Study : High rise towers

Various forms of high-rise towers were assessed to attempt to enhance ventilation performance (Fig 12,13). The effect on ventilation performance of surrounding similar scale buildings was also investigated. Strategies included inducing fresh air intake from both the upwind and downwind facades using low pressure hollow cores. Wind deflectors at the top and bottom of the building can enhance performance. However the scale of the devices become large, and to be useful they must essentially become part of the building form.

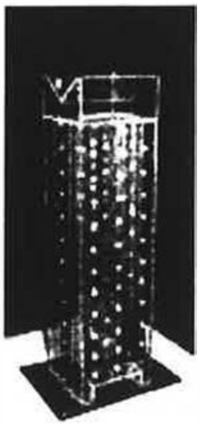
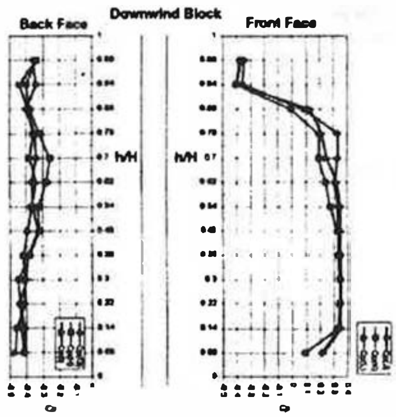


Figure 12 (left): High rise building with hollow cores and wind catchers.

Figure 13 (right): Example of Cp variation with height at front and rear of building.



Case Study: Chimney outlets

This natural ventilation strategy used communal chimneys (Fig 14). The chimney design features were based on the Ionica and De Montfort building exemplars. Results of initial tests indicated that cross flow patterns between floors and rooms would occur under wind conditions, i.e. that the chimney plenums would provide a route of waste air entry to other rooms. Tests were made on variants of roofscape, building form and chimney termination, in order to develop a design capable of producing a consistent flow regime for different wind directions. Ventilation performance was assessed using a network flow model, BREEZE 6, calculating summer and winter conditions. The form of the building was seen to introduce far greater variation in results than the form of the outlet termination; a monopitch roof, for instance, introduced a wind directionality, significantly reducing ventilation performance in parts of the building.

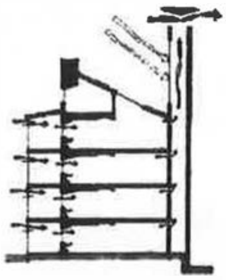


Figure 14 : Section of design, showing ventilation strategy

Case Study : H-pot chimneys

This study tested a naturally ventilated theatre (Fig 15), designed by Short Ford Associates, using H-pot chimneys as outlets. The study aimed to determine the optimum performance for the devices. The wind tunnel studies indicated that the H-pot devices could retain a negative 'suction' pressure performance relatively independent of wind direction (Fig 16), the building being flanked on one side by a large building block. The design included low level inlets, which were wind direction dependant, and although the overall pressure gradients were favourable, the study highlighted the problem of locating low level inlets with respect to wind effects.

Figure 15 (left): Model of theatre in wind tunnel, with surrounding buildings.

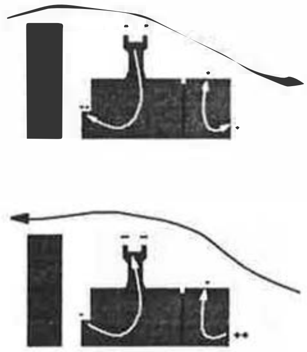


Figure 16 (right): Schematic indicating the pressure gradients between inlets and outlets for two wind directions.

Comparing CFD and wind tunnels

External wind flow

Currently the analysis of external wind flow and internal air flow for a building are carried out separately. External wind flow can be carried out in a wind tunnel or by CFD modelling. A comparison of wind tunnel and CFD for the Saga HQ (Figs 17 and 18) indicate close similarity between the two methods.

Figure 17 (left): Smoke Visualisation of wind flow over the building.

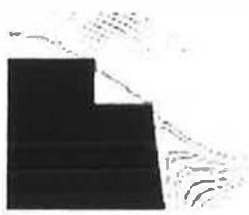


Figure 18 (right): CFD calculation of wind flow over the building.

In practice however wind tunnels seem to offer some advantages for designers over CFD. In particular, scale modelling is more tangible and it is easier to visualise flows in three dimensions and to carry out minor modifications. Generally, from the experience of working with designers in this project, there is a positive affinity by designers to wind tunnel tests.

Internal air flows

Wind tunnel scale modelling cannot be used to investigate internal air flow, and the only credible option which will consider both buoyancy and momentum boundary conditions is CFD modelling. For natural ventilation, pressure boundary conditions are required, using Cp values from wind tunnel tests. So, a typical design investigation might combine wind tunnel and CFD modelling. An example of the Saga HQ CFD simulation with the modified 'wing deflector' outlet is presented in Fig 19. This illustrates a successful ventilation strategy for the prevailing wind direction.

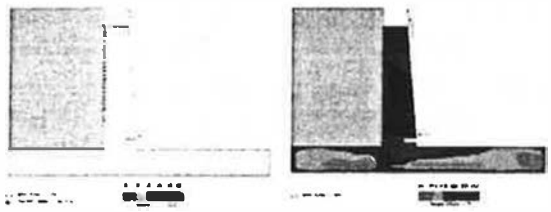


Figure 19 : CFD prediction of airflow (left) and temperature distribution (right) in the Saga HQ atrium.

Porosity

The application of Cp values in CFD or network calculations may require modification if used with large openings. Cp values for solid bodies will be different from those of highly porous forms (i.e. ones with large open windows), and the flow patterns around and within the building will be altered. LDA measurements were carried out to obtain Cp values for a building block for a range of porosity. These showed that correction factors to Cp values applied to porous facades could be large (between 40% and 70% for porosity (facade open area) between 18% and 45%).

Conclusions and guidelines

- Wind effects should be considered in natural ventilation design. They may dominate stack effect, especially in summer when internal external air temperature differences are generally smaller. The 'buoyancy case' should not be assumed to be worst case.
- Prevailing wind conditions should not be used in isolation, shifts in wind direction can alter flows dramatically and possibly defeat ventilation strategies.
- In designing for wind effects, the building form and its context in relation to surrounding buildings dominates over any fine detail of ventilation devices. Inlet/outlet devices designed to enhance performance must be viewed in this context. Such devices will only work if the building form is appropriate.
- Ventilation strategies that require a specified flow path (i.e. definite inlet and outlets) will be difficult to make robust against wind directionality. Those strategies that can stand inlets acting as outlets and visa-versa will be more successful.
- Sharp edges (ridges, corners) will cause zones of low pressure, and turbulent air downwind. Devices located in such zones may not act as intended. Zones will alter position for changes in wind direction.
- Outlets (suction) devices can be directional or 'omnidirectional' with respect to wind direction. If they are directional they need to be located in low turbulence 'clean wind' locations, especially if they are to account for changes in wind direction.

- Outlet devices can be 'tuned' to wind direction (for a suitable building form), for example, using shields, and deflectors, to improve their performance.
- 'Monodraught' or wind catching devices can be utilised, but may be wind direction sensitive. They may only work for zones where flow reversal is not problematic.
- Omnidirectional (e.g. H-pot) devices are suitable for outlets in more turbulent locations to maintain suction with changes in wind direction.
- Inlet (positive pressure) devices are more difficult to locate and tune for optimum performance. There may be situations where they will incur negative pressures. In such cases the pressure gradient between the inlet and outlet should be assessed to ensure that it promotes air flow in the required direction.
- Wind tunnel or CFD can be used to estimate pressure coefficients and to visualise air flow. The wind tunnel is a useful tool, allowing qualitative as well as quantitative assessment of wind ventilation performance. It can be easily applied in design due to ease of modification of models. The interaction with designers may occur more readily than with computer methods.
- Cp values from wind tunnel tests can be used to establish pressure boundary conditions for CFD and zonal (network) models, in order to predict internal air flows and ventilation rates.
- When dealing with large openings Cp values should be adjusted for 'porosity' effects.

Bibliography

"The Effects of Building Form on the Natural Ventilation of Commercial Buildings", D.K.Alexander, H.G.Jenkins, P.J.Jones, Proceedings 17th AIVC conference, Gothenburg, Sweden, pp571-578.

"A Comparison of Wind Tunnel and CFD Methods Applied to Natural Ventilation Design", D.K.Alexander, H.G.Jenkins, P.J.Jones, accepted for IBPSA Building Simulation '97, Prague.

The following higher degree students contributed to the project, under the supervision of the project team.

Ms. C.Oliver, "The Assessment of the Robustness of a Strategy which Assists and Enhances Natural Ventilation by the Manipulation of the Building Form", MSc dissertation, September 1995, University of Wales.

Mr. I.Jones, "The Performance and Potential of Wind Chimneys as a Component of the Ventilation Strategy for Commercial Buildings", MSc dissertation, September 1995, University of Wales.

Dr. A.M.Ishmial, "Wind Driven Natural Ventilation in High-rise Office Buildings with Special Reference to the Hot-humid Climate of Malaysia", PhD thesis, August 1996, University of Wales.

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Closing the action/ awareness gap: applying limiting factors theory to individual environmental action

Neil Bowman & Jane Goodwin, De Montfort University[1], and Phil Jones, Nigel Vaughan & Nikki Weaver, University of Wales[2]

Summary

The aim of this research is to identify the factors that limit people's participation in waste recycling schemes and to assess what combination of factors are necessary to encourage people to recycle a greater proportion of their domestic waste. The research is designed as an intervention study, whereby changes in attitudes and behaviour are monitored both prior to, and after, a campaign which is aimed at altering levels of recycling. A pilot questionnaire was administered to 10 different socio-demographic classification groups in Cardiff and 8 in Leicester. If the pilot study proves to be an accurate reflection of the attitudes of participants in the main study, then motivation and information are likely to be important factors in affecting whether an individual decides to recycle or not.

Background

There has undoubtedly been an increase in public awareness of environmental issues in recent years (Trudgehill, 1990). Most people now believe there is a need to protect the environment and to safeguard it against further degradation and destruction. However, whilst the majority of people agree, at least in principle, in the need to take environmental action, many do not take action themselves (Atkinson and New, 1993). People's good intentions do not always translate into action and thus a gap exists between people's attitudes and behaviour towards the environment.

The aim of this research is to identify the factors that limit people's participation in waste recycling schemes and to assess what combination of factors are necessary to encourage people to recycle a greater proportion of their domestic waste.

This project is unique in that it applies biological limiting factors theory to environmental action and in doing so looks at the major factors that influence whether or not an individual takes environmental action. The theory states that by appraising and supplying the factors that limit growth, growth can be maximised using minimum resources (Fogg,1963). For the purpose of this project, waste recycling is being used as a practical example and as a means of testing biological limiting factors theory, though the theory is equally applicable to other fields such as energy. The theory is being tested by investigating participation in the recycling of domestic waste in kerbside collection areas in the cities of Leicester and Cardiff.

The measurable objectives are to:

- identify the major factors that encourage people to increase the amount of domestic waste they recycle;
- prepare a set of guidelines for waste management planners; and
- increase the amount of waste recycled in case study cities, ensuring that more added value is achieved for local authority expenditure.

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The research is being carried out by a team of investigators from the University of Wales, Cardiff, and De Montfort University, Leicester. The Universities are working in close collaboration with Cardiff County Council and Leicester City Council, both of whom are very active in the field of waste recycling. Both local authorities are highly committed to providing a comprehensive recycling service to the public.

Research design

The research is designed as an intervention study, whereby changes in attitudes and behaviour are monitored both prior to, and after, a campaign which is aimed at altering levels of recycling. The focus of the campaign will be determined by the factors identified in the main survey. The study is being undertaken by means of both a literature review and survey work.

The are five main stages to the project:

- literature review;
- pilot survey;
- pre-test survey; Monitoring of
- intervention tests;
- post-test survey. behaviour

The literature review identified three main factors which are:

- convenience;
- motivation/attitude; and
- information.

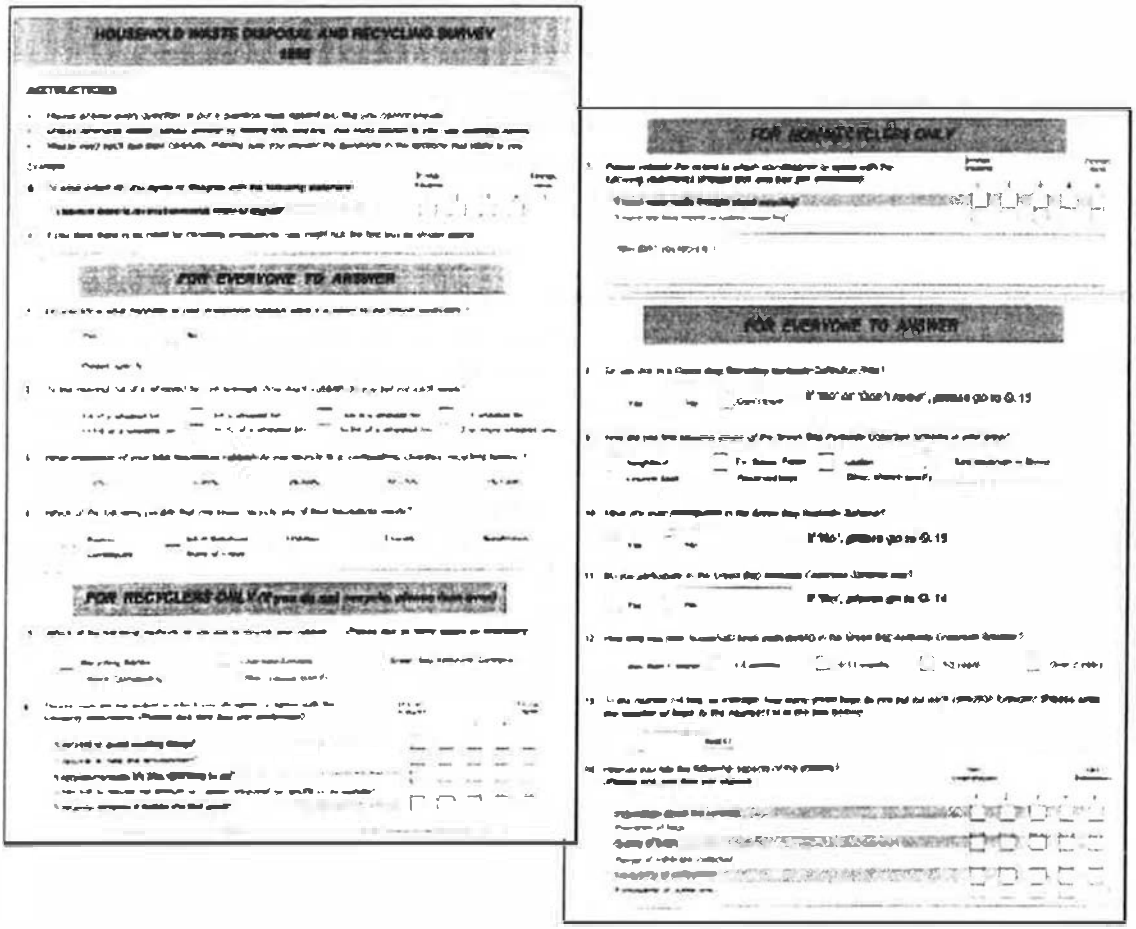
Previous research (Judge & Becker, 1993, Coggins & Brown, 1992) has revealed that 'convenience' is a highly significant factor influencing participation in recycling. Given this, the research will focus on areas in receipt of the kerbside collection scheme, which is considered to be the most convenient method of recycling. As convenience is being held constant throughout the project, it is possible to concentrate on evaluating the role of the other limiting factors, that is, information, attitude and motivation.

It was apparent from the literature that a range of factors govern behaviour and these factors vary in significance between different socio-demographic groups. Studies have shown that recyclers and non-recyclers differ in their level of education and the amount of information they have (Vinning and Ebreo,1990). The largest single group of recyclers have been found to be those with at least 7 to 12 yrs of education (Lansana, 1992). Other socio-demographic factors identified from the literature review include age, income, gender and occupation. The influence of socio-demography on recycling participation is also being investigated in this research.

The pre-test survey, administered last December by means of a questionnaire, was constructed using the limiting factors identified in the review. The questionnaire was designed to elicit current attitudes, motivations, knowledge and practices relating to household waste disposal and recycling, in addition to some wider environmental themes. Subsequent analysis will reveal and assess the relative influence of various limiting factors on recycling behaviour. A pilot study was undertaken prior to the pre-test survey in order to determine the reliability and validity of the questionnaire.

During the intervention stage, several experiments will be conducted in an attempt to influence recycling behaviour in the two cities. Possible measures include the recruitment of local 'recycling representatives', to provide encouragement, information and guidance to their neighbours on recycling.

Other measures could involve setting recycling goals in local areas, and administering rewards for improved levels of recycling. It is anticipated that the intervention may comprise a number of distinct experimental conditions which will be administered to different socio-economic groups. The exact nature of the experimental conditions will be determined by the findings from the main survey which are expected in the Spring of 1997.


HOUSEHOLD WASTE DISPOSAL AND RECYCLING SURVEY

FOR EVERYONE TO ANSWER

FOR RECYCLERS ONLY

FOR EVERYONE TO ANSWER

Figure 1: The questionnaire

The post-test questionnaire survey will be administered in September 1997 to assess the effectiveness of the intervention study .

People's participation in the kerbside collection recycling scheme will be monitored on a bi-weekly basis throughout the intervention period as past research has shown that some discrepancies exist between self-reported behaviour and actual behaviour (DeYoung, 1990). As the majority of previous interventions studies (e.g. Burn & Oskamp, 1986) have been conducted over a period of four to six weeks, it is intended that these interventions should last for a minimum of six months in order that recycling behaviour has a greater chance of becoming habitual.

Sampling

Since individuals will express different attitudes and responses to the experiments, it is important to ensure that the surveys and experiments are administered to a sample population which reflects the different socio-demographic characteristics in Cardiff and Leicester. Previous research has tended to focus on predominantly white middle-income groups (DeYoung, 1990), and students (Allen et al, 1993, Barker et al, 1994). Therefore, for the purpose of this study, respondents are being selected to represent a wider range of socio-demographic groups in Cardiff and Leicester.

The pilot study

The pilot sample was selected by applying 'GB Profiler', developed at Leeds University, to GIS software. GB Profiler provides each enumeration district in Cardiff and Leicester with a socio-demographic classification code and description, based on OPCS Census data collected in those areas. The information was incorporated into a GIS system (MapInfo). Socio-demographic data was mapped onto Ordnance Survey maps of the two cities and each kerbside collection area was digitised. This procedure was used to spatially view the socio-demographic information in order to select and mirror the samples within each city.

The pilot questionnaire was administered to 10 different socio-demographic classification groups in Cardiff and 8 in Leicester. The effectiveness of 3 types of survey administration techniques were assessed for use in the main study. A postal questionnaire with hand collection was considered to be the most effective method for securing responses from both recyclers and non recyclers for the main survey.

The results of the pilot study supported the theory that attitudes are not consistent with behaviour. For example, stated environmental concern did not differ significantly between recyclers and non-recyclers. The pilot study identified a number of other limiting factors local to residents in Leicester including opposition to having a bi-weekly collection of general waste. Motivation was found to be a highly significant factor in determining recycling behaviour. Other factors such as information were also found to play an important role in affecting recycling levels.

Conclusion

As many people rejected the idea of financial rewards in the pilot study, it is unlikely that extrinsic incentives will be employed in the intervention study. The use of goal setting and feeding back information may be a more effective alternative to increasing recycling levels. If the pilot study proves to be an accurate reflection of the attitudes of participants in the main study, then motivation and information are likely to be important factors in affecting whether an individual decides to recycle or not.

Limitations to the scope of the research project are recognised, however, it is intended that the intervention study will provide guidance to waste planners and policy makers when designing future kerbside recycling schemes.

References

Allen, J., Davis, D., and Soskin, M. (1993) 'Using Coupon Incentives in Recycling Aluminium - A Market Approach to Energy Conservation Policy'. *Journal of Consumer Affairs*, vol.27, no.2, pp.300-318.

Atkinson, W. and New, R (1993) 'Kerbside Collection of Recyclables from Household Waste in the UK - a Position Study'. Warren Spring Laboratory.

Barker, K., Fong, L., Grossman, S., Quin,C. et-al. (1994) 'Comparison of Self-Reported Recycling Attitudes and Behaviors with Actual Behavior' in *Psychological Reports*, Aug Vol.75, no.1, Pt 2, Spec Issue, pp.571-577.

Burn, SM., and Oskamp, S. (1986) 'Increasing Community Recycling with Persuasive Communication and Public Commitment'. *Journal of Applied Social Psychology*, vo.16, no.1, pp.29-41.

Coggins, PC., and Brown, R. (1992) *Recycling Schemes: Drop-Off (Bring) Systems, Public Participation Surveys*, (Report under Contract to Warren Spring Laboratory), Luton: Luton College of Higher Education.

De Young, R. (1990) 'Recycling as Appropriate Behavior: A Review of Survey Data from Selected Recycling Education Programs in Michigan'. *Resources Conservation and Recycling*, Jun vol.3, no.4, pp.253-267.

Fogg, G.E. (1963) 'The Growth of Plants. Penguin

Judge, R., and Becker, A. (1993) 'Motivating Recycling - A Marginal Cost-Analysis'. *Contemporary Policy Issues*, vol.11, no.3, pp.58-68.

Lansana, FM. (1992) 'Distinguishing Potential Recyclers from Nonrecyclers: A Basis for Developing Recycling Strategies'. *Journal Of Environmental Education*, Winter Vol.23, No.2, Pp.16-23.

Trudgehill., S.T. (1990) 'Barriers to a Better Environment'. Belhaven Press, London

Vining, J., and Ebreo, A. (1990) 'What Makes A Recycler? A Comparison of Recyclers and Nonrecyclers'. *Environment and Behavior*, Jan vol.22, no.1, pp.55-73.

Empirical validation of the glazing models in thermal simulation programs of buildings

Herbert Eppel & Kevin Lomas, De Montfort University[1]

Abstract

Buildings are employing progressively higher levels of glazing on their outer facades. Heat gains by solar radiation and the heat losses due to longwave radiation and convection dominate the thermal characteristics of the glass. Detailed thermal simulation programs are often called upon to predict the heating energy demands and internal temperatures in highly glazed spaces. Previous work had shown that the algorithms that constitute the models of glazing systems may differ such that they have a large impact on program predictions. This paper describes work to evaluate the glazing models in three thermal simulation programs, using validation data from Test Room 3000. There was a general tendency for the internal convective heat flux to be underestimated by the algorithm of Alamdari & Hammond, which resulted in an underprediction of heating energy demands by ESP. Eight validation data sets were produced and these have been documented.

Introduction

Sealed glazing systems occupy ever greater proportions of the external envelope of non-domestic buildings. The UK government currently advocates the use of daylight as a way of reducing energy consumption in non-domestic buildings [1], and is exploring the benefits of low U-value glazing systems. In the domestic sector, passive solar design is being promoted as a cost effective method of reducing energy consumption [2]. The energy consumption of, and the thermal environment within, both domestic and non-domestic buildings are often dominated by the thermal performance of the glazing system.

Detailed thermal simulation programs are widely used to predict the thermal performance of buildings, however, they employ different models of the glazing. Extensive program validation work at De Montfort University (DMU) and elsewhere has shown that these differences result in divergent predictions even for modestly glazed spaces [3,4].

To study the performance of glazing systems under real weather and room operating conditions, the Energy Monitoring Company (EMC) operates an outdoor test facility. Using data from this test facility, the objectives of this EPSRC funded project were to:

(a) evaluate the accuracy of the native glazing models embedded in at least three well known public sector programs: ESP [5,6]; HTB2 [7] and SERI-RES [8];
(b) to evaluate, by direct measurement, the accuracy of the external and internal longwave radiation and surface convection algorithms;
(c) to evaluate the accuracy of short-wave solar transmission algorithms; and
(d) to produce at least 6 well documented data sets which can be made openly available for validating glazing models.

This paper provides an overview of the work and describes some results.

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Simulation of glazings

The glazing models used by thermal programs differ significantly in their complexity. Simple models employ concepts such as solar aperture and U-value for solar gain and heat loss calculations. More sophisticated models rely on the correct operation of a number of component algorithms. These involve accurate evaluation of: convective exchange at internal and external surfaces, longwave exchange at the inside & outside surfaces and convective and longwave exchange in cavities between glazing panels (Figure 1).

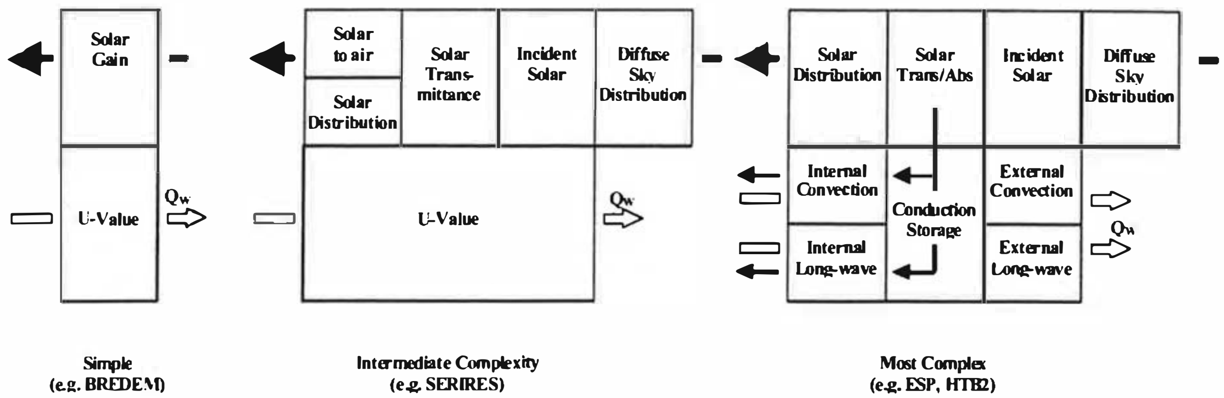

Figure 1: Glazing model algorithms of different complexity

Internal convective heat transfer coefficient (ihtc) algorithms employed in DSPs vary significantly and have a marked influence on the predicted performance of glazed spaces [3,4,9]. Some laboratory work to measure ihtc's [10] has shown that conventional ihtc values, as found for example in the CIBSE guide [11], may be significantly in error.

The algorithms dealing with internal longwave exchange to the glazing are also important [12]. However, the fundamental physics is well understood and can, with effort, be modelled exactly, e.g. by a radiosity or ray-tracing approach. Errors arise due to the approximations made in thermal simulation programs, e.g. to reduce calculation times.

The lack of confidence in extant external heat transfer coefficient algorithms led the EPSRC to support work in this area. The results of the project were published recently [13,14,15]. Convection and longwave exchange across the cavities in glazing systems has a large impact on the heat losses through low U-value windows. The coating on the glazings, the cavity widths, and the type of gas fill all influence the heat flux [16].

It is clear that changes to the component algorithms in a glazing model can, individually, have a noticeable effect on the predictions obtained from the complete thermal simulation program. Since, in the complete program, all the algorithms are operating simultaneously, the total effect on predictions is likely to be even more pronounced. This project sought to understand the influence of individual algorithms as well as the total influence when they are combined in the way that is adopted by the latest versions of ESP, SERI-RES and HTB2.

Measurement of glazing properties

A high performance window test facility, called Test Room 3000 [17], was built by the Energy Monitoring Company (EMC) in 1990 (Figure 2). The facility is the same size as a typical room and so realistic thermal regimes can be established. There is one glazed façade which can contain any glazing system. The back-loss from the room can be controlled or totally eliminated by heating the air in the surrounding cavities (Q_B=0). Infiltration was completely eliminated (Q_A=0). All internal walls were thermally light-weight thereby avoiding the complexities introduced by long thermal time constants. The facility was completely unshaded and on an unobstructed site. The net heat flux (Q_{net}) through the glazing is given by

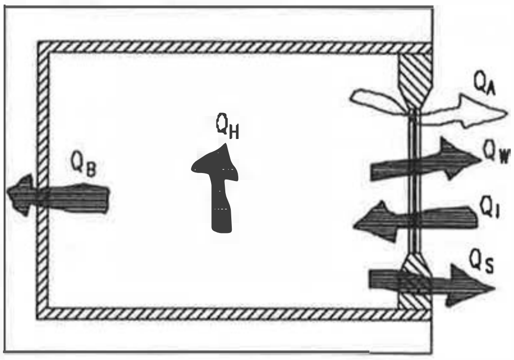

Fig. 2: Schematic diagram showing heat flows in Test Room 3000

$$Q_{net} = Q_W - Q_I = Q_H - Q_S$$

where
Q_W = heat loss through the glazing;
Q_I = solar gain;
Q_H = heater output;
Q_S = heat loss through south wall.

In the experiment, Q_H and Q_S were measured and so the net heat flux could be deduced. At night Q_I = 0, and so the actual heat loss through the glazing could be found. Detailed temperature measurements allowed the individual convective and radiant components of this to be obtained.

Error analysis showed that Test Room 3000 could, in principle, measure the net heat flux through glazing to an accuracy of better than ±5% even for systems with U-values as low as 1.0 W/m²K [17]. Test Room 3000 therefore offers: (a) the opportunity to accurately quantify the thermal behaviour of high performance glazing systems; and (b) the possibility of measuring the heat fluxes through glazings and at their surfaces. The project sought to establish whether the potential of the facility could be realised in practice and thus that the data could be used to validate thermal simulation programs.

In this project, 8 experiments were undertaken. The glazing systems tested and the dates and duration of the experiments are shown in Table 1.

Exp. Code	Glazing System[1]	Date of Exp.[3]	Duration (days)	U-Value [W/m²K] Assumed	Measured
1	Opaque Panel	15:2 - 24:2	10		
1a	Opaque Panel[2]	27:2 - 01:3	3		
2	Single	06:3 - 17:3	12	5.5	5.21
3	Double - 6mm cavity	25:3 - 3:4	10	3.1	2.93
4	Double - 12mm cavity	21:4 - 30:1	10	2.7	2.4
5	Double - 12mm cav., 1 low-e layer	11:5 - 22:5	12	1.9	1.73
6	Double - 12mm cavity, 1 low-e layer, argon filled cavity	24:5 - 3:6	11	1.6	1.6
7	Triple - 12mm cavities, two low-e layers, argon filled cavities	9:6 - 16:6	8	0.9	0.93

[1] Nominal glass thickness 6mm for all systems
[2] Room setpoint 28°C, cavity set-point 22°C : in all other experiments cavity and room set-point 25°C
[3] All experiments in 1995

Table 1: List of Experiments

Inferred window U-values

To determine the on-site U-values of each glazing system, the deduced flux per unit area through them was plotted against the temperature difference at each night-time hour when the room air set-point was within ±0.1°C of 25°C (e.g. Figure 3). All regression lines passed very close to the origin; the correlation coefficients were 0.61 or better; and except for single glazing, the correlation coefficients got smaller, i.e. a worse correlation, as the glazing U-value decreased. This effect might be expected because it is more difficult to deduce Q_w, and hence U-values, when the absolute flux through the glazing is smaller. The greater scatter for the single glazing may be because the fluctuations in surface heat transfer coefficients are causing genuine differences in the U-value. (The resistance to heat flow is almost entirely due to their surface resistances).

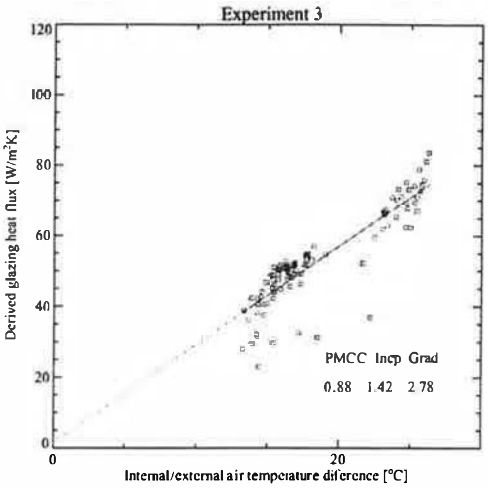

Fig. 3: Comparison of derived heat flux through the glazing with the temperature diff. across it

The U-values assumed in the simulations were based on manufacturers' data. These were compared with the slope of the graphs, i.e. the measured values (Table 1). The assumed values had the same rank ordering as the measured values. Using the measured values derived by forcing the regressions through the origin, the difference from the assumed values was up to 0.30 W/m²K, i.e. a difference of about 0.7W per °C temperature difference. Because the assumed U-values were between 6% and 13% above the values assumed in the simulations for experiments 2 to 5, one would expect the predicted heating energy demands to be above, rather than below, the measured values. The whole model comparisons explore this issue further.

Whole model comparisons

ESP predicted hourly energy demands in all the experiments which were lower than those predicted by the other programs. These differences can be attributed directly to the differences in the algorithms adopted by the programs. The ESP predictions were also virtually always lower than the measured heating energy demands and by considerably more than the 2.5% assumed total uncertainty (e.g. Figure 4). In all the experiments (except 3) HTB2 predicted heating energy demands which were closer to the measurements than the predictions of the other two programs. (In Experiment 3, SERI-RES and HTB2 produced similar results). SERI-RES tended to predict the highest energy demands, and these exceeded the measurements in all the experiments except 1a. The higher U-values assumed in the simulations could explain this.

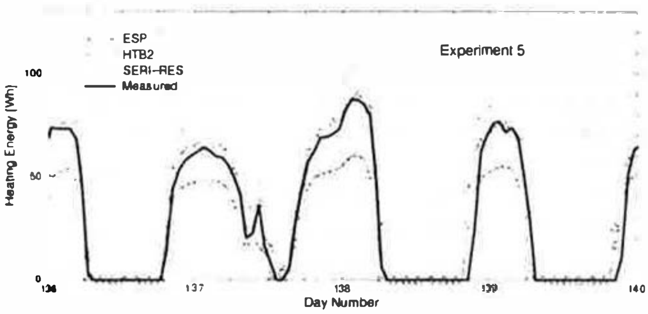

Fig. 4: Typical hourly heating energy results

In the recent IEA 12/21 empirical validation exercise [18], ESPv7.7a, HTB2v1.2, HTB2v1.10 and SERI-RESv1.2 were all used to predict the heating energy demands of intermittently heated test rooms located on the EMC test site. Rooms with either double or single glazing or no glazing at all, were studied. For the double glazed and opaque rooms, the predictions were also compared with field measurements. In those tests, ESP also predicted heating energy demands which were lower than those predicted by the others and also below the measurements. Similarly, in empirical validation work using data from a double glazed, passive solar test building at the National Institute of

Standards and Technology, ESP-r predicted lower energy demands than HTB2 and SERI-RES. The predictions were also significantly below the measured values [19].

The results from this study are thus very similar to those seen in previous work. In this work, detailed measurements were made so it was possible to study the performance of the component algorithms in the glazing models to shed light on the reasons for the differences in predictions.

Example of algorithm validation

The procedure used to evaluate individual algorithms will be illustrated for ESP and results shown. Prior to evaluation, the diagnostic output from the program was checked. The output for each experiment was tested to ensure that it produced an energy balance for the whole room, and to ensure that the sum of the convective and longwave fluxes at each surface of the glazings were equal to the total predicted flux. The excellent agreement which was produced for all the experiments indicated that the ESP results are internally consistent [e.g. Figure 5]. The measured and predicted heat fluxes at internal and external surfaces were compared with the values measured at night in experiments 2 to 4. In those, the fluxes were greater and so less susceptible to experimental error.

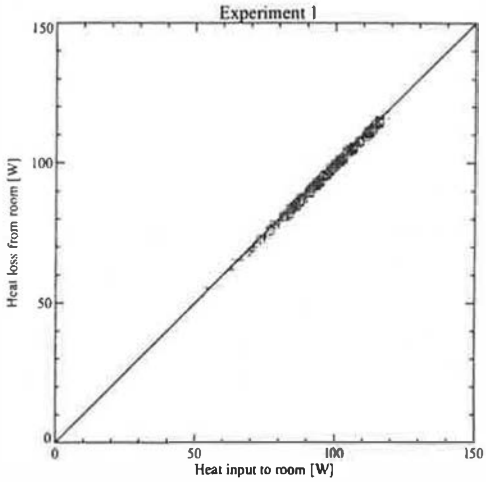

Fig. 5: ESP room energy balance

Heat exchange at external surfaces

The external convective heat flux predicted by ESP was generally lower than the measured value in the experiments where double glazing was installed (under conditions of high heat flow). This was reflected in the lower predicted external convective coefficients, particularly in the experiments with double glazing. These results are consistent with the low heating energy demand predictions of ESP compared to the measurements. In contrast, the predicted external heat flux due to longwave radiation was generally higher than the measured values. This counteracted the higher convective losses and so the total heat flux from the external surface, and hence the deduced external combined surface coefficient was similar to the values inferred from the measurements (Figure 6).

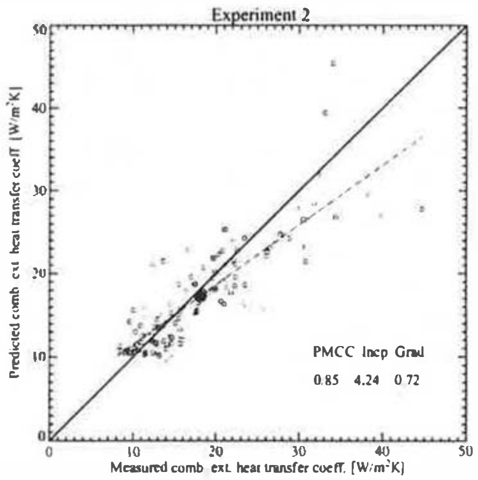

Fig. 6: Comparison of measured and predicted external combined coefficients

Heat exchange at internal surfaces

The measured internal longwave exchange between the glazings and the inner surfaces of the room was calculated, and by dividing by the difference between the window surface temperature and the air temperature, an effective longwave exchange coefficient could be deduced. Such a value could also be inferred from the diagnostic ESP output. The room was rectangular with all internal surfaces at the same constant temperature, so the internal longwave exchange could be calculated as 4.7 W/m²K. In the experiments, the differences between the measured and predicted heat fluxes were generally small with a slight tendency for, on average, over- rather than under-prediction of fluxes. However, when the magnitude of the fluxes was greatest (which occurs under conditions of peak heating energy demand) the predicted fluxes were close to the measurements.

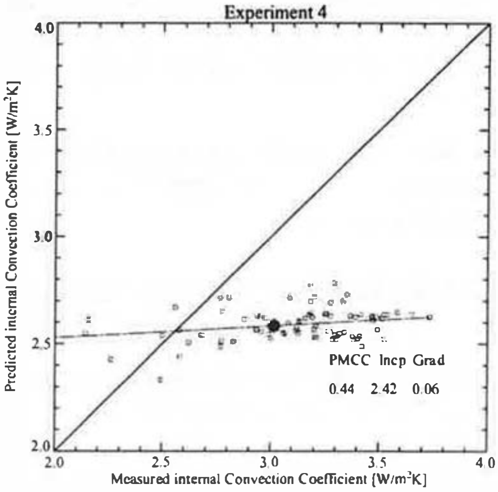

Fig. 7: Comparison of measured and predicted internal convection coefficients

The predicted internal convection coefficients were invariably lower than the measured values. The predicted values were between 2.4 and 2.8 W/m²K in the double glazed rooms, whereas measured values were generally between 2.4 and 4.2 W/m²K (Figure 7). The higher values occurred under cold conditions, and so the measured heating energy demands were likely to be greater than the predicted values. The predicted values did not correlate well with the measured ones, having a regression line of almost zero gradient.

The internal heat transfer coefficients were numerically smaller than the external coefficients, and so they had a larger impact on the overall resistance of the glazing to heat flow than the external coefficients. It is evident that the lower heating energy demands predicted by ESP could be largely due, in this room, to the convective heat transfer coefficient being lower than the measured values. It is worth noting here that the measured average convective coefficient of 3.0 to 3.4 W/m²K is close to the standard CIBSE value of 3.0 W/m²K [11]. As noted above, the average ESP value was much lower.

To investigate further, the ESP default algorithm (after Alamdari & Hammond [20]) was replaced with an alternative algorithm (after Khalifa and Marshall [10]) and the simulations repeated. The algorithm predicted values from 2.6 W/m²K to 3.5 W/m²K which was much closer to the measured mean values. As a consequence, ESP produced higher heating energy demand predictions than previously obtained and these were much closer to the measured values. It was beyond the resources of this work to investigate these matters further, however, the primary reason for the low heating energy demand predictions of ESP observed in this, and in other research work, appears to be due primarily to the low internal heat transfer coefficient values.

The eight data sets from Test Room 3000 have been made available electronically and a site handbook has been produced so that others can use the data effectively.

Conclusions

1. Dynamic thermal simulation programs play an important role in the design of energy efficient UK buildings. This is likely to remain so for the foreseeable future. Differences in their numerical predictions are likely to be due to the algorithms of which the glazing models are comprised. The algorithms may also produce heat flux predictions which are different from those which actually occur in real buildings.
2. Test Room 3000 is an experimental facility which has been shown to be capable of measuring the U-value of glazing systems exposed to real weather conditions. It can also provide data to validate thermal simulation programs.

3. Of the three programs tested (ESP, HTB2 and SERI-RES), ESP predicted heat fluxes through the glazing which were lower than the measured values, whilst, on some occasions, SERI-RES predicted marginally higher fluxes. The ESP predictions are consistent with work reported elsewhere.
4. The lower ESP predictions were attributed to the algorithm used to predict convective heat flux at internal surfaces. An alternative algorithm provided predictions which were much closer to measured values.
5. The eight data sets from Test Room 3000 have been made available electronically and a site handbook has been produced so that others can use the data effectively.
6. Vendors and users of simulation programs have given a high priority to validation. This work is a further contribution to these efforts.

Acknowledgements

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References

1. Crisp, V.H.C., Littlefair, P.J., Cooper, I. and McKennan, G. (1988) Daylighting as a passive solar energy option: an assessment of its potential in non-domestic design, Building Research Establishment report BR 129, BRE, Garston.
2. Yannis, Simos (1994) Solar energy and housing design, Vol.1: Principles, Objectives, Guidelines, 146pp., Vol 2: Examples, 127pp., ISBN 1 870890 45 0
3. Lomas, K.J. et al (1989) Applicability Study 1: A UK initiative to determine the error characteristics of detailed thermal simulation models, Proc. Science & Technology at the Service of Architecture, Paris, France, pp 559-563.
4. Lomas, K.J. (1992), Applicability Study 1, Executive Summary, Rep. to Energy Tech. Support Unit, DTI, School of Built Environment, De Montfort Univ., 73-pp.
5. ESRU (1995) A building energy simulation environment, User Guide, Version 8 Series, ESRU Manual U95/1. Energy Systems Research Unit, Univ. of Strathclyde, Glasgow.
6. ESRU (1994) Summary of ESP-r's product model, Technical Report. ESRU Report TR94/10. Energy Systems Research Unit, Univ. of Strathclyde, Glasgow.
7. Alexander D.K. (1992) HTB2 - A model for the thermal environment of buildings in operation, User Manual. Welsh School of Architecture, UWCC, Cardiff.
8. Palmiter, L. and Wheeling, T. (1983), Solar Energy Research Institute residential energy simulator version 1.0, Solar Energy Res. Inst. Golden, CO, USA, 365pp.
9. Clarke, J.A. (1991), Internal convective heat transfer coefficients: a sensitivity study, ESRU Rep. to ETSU on Proj. E/5A/1304/2255, 40-pp.
10. Khalifa, A.J.N. and Marshall, R.H. (1990), Validation of heat transfer coefficients on interior building surfaces using a real-sized indoor test cell. Jnl. Heat Mass Transfer, Vol. 33, No. 10, pp.2219-2236.
11. CIBSE Guide (1986) Vol. A: design data, The Chartered Institution of Building Services Engineers, London.

12. Stefanizzi, P., Wilson, A. and Pinney, A. (1990), Internal long-wave radiation exchange in buildings: Comparison of calculation methods: II Testing of algorithms. Building Services Eng. Res. & Tech., Vol. 11, No. 3, pp87-96.

13. Loveday, D.L. and Taki, A.H. (1996) Convective heat transfer coefficients at a plane surface on a full-scale building facade. Int. Jnl. Of Heat and Mass Transfer, Vol. 39, No. 8, pp 1729-1742.

14. Taki, A.H. and Loveday, D.L. (1996) Surface convection coefficients for buildings facades with vertical mullion-type protrusions. Proc. Inst. Of Mech. Eng., Vol. 210, pp 165-176.

15. Taki, A.H. and Loveday, D.L. (1996) External convection coefficients for framed rectangular elements on building facades. Energy and Buildings, Vol. 24, pp 147-154.

16. Muneer, T. (1996) Multiple glazed windows: Design charts, Proc. Building Services Engineering Research and Technology, Vol. 17, No. 4, pp 223-229.

17. Martin, C. and Watson, M. (1989), Design of a test facility for the investigation of high performance windows. Energy Monitoring Company, 19-pp.

18. Lomas, K.J., Eppel, H., Martin, C. and Bloomfield, D. (1994) Empirical validation of thermal building simulation programs using test room data, International Energy Agency Energy Conservation in Buildings and Community Systems Programme, Annex 21: Calculation of Energy and Environmental Performance of Buildings and Solar Heating and Cooling Programme, Task 12: Building Energy Analysis and Design Tools for Solar Applications; Vol. 1, Final Report, 141-pp; Vol. 2, Empirical Validation Package, 78-pp; Vol. 3, Working Reports, 94-pp.

19. Eppel, H. (1995), Empirical validation of three thermal simulation programs using data from a passive solar building, MPhil thesis, De Montfort University

20. Alamdari, F. and Hammond G. (1983) Improved data correlations for buoyancy-driven convection in rooms. Building Services Engineering Research and Technology, Vol. 4, pp 106-112.

A Dynamic Lighting System: background and prototype

Paul Cropper, Kevin Lomas, Arthur Lyons and John Mardaljevic, De Montfort University[1]

Abstract

Using natural light it is possible to significantly reduce the reliance on - and hence the electrical energy consumption of - artificial lighting installations in non-domestic buildings. The higher efficacy of natural light also lowers the level of internal heat generation and thus reduces the electrical energy consumption of air conditioning systems. Unfortunately at present it is not possible to accurately predict time-varying illuminance in geometrically complex spaces lit by any combination of natural and artificial lighting arrangement and lighting control system. A computerised Dynamic Lighting System (DLS) for doing this is described along with some initial validation results. The system should be capable of accurately predicting time-varying illuminances, the status of artificial lights and their energy demand.

Introduction

In an increasingly energy conscious world, architects and designers are experimenting with innovative building design and glazing systems to reduce overall energy consumption. By using natural light it is possible to significantly decrease the use of artificial light, reducing not only the energy consumed by lighting but also that consumed by air-conditioning required to remove excess heat.

It is possible to predict internal illuminances, using either scale models and an artificial sky, or computer modelling. However, the cost of making accurate scale models can be high, and most artificial skies are limited in there capabilities, particularly in the range of luminance they can provide. Computer modelling is more flexible, and can accommodate a mix of natural and artificial sources, therefore it can take several minutes (or longer) to calculate the illuminance at a single point when there are complex inter-reflections. This time penalty may not be significant if only a few values are required, but to examine how illuminance changes over long time periods, e.g. hourly interval throughout a year, simulation times can be prohibitive. The *daylight coefficient* approach, developed by Tragenza and Waters [1], will, in principle, allow computer modelling to be used whilst keeping simulation times manageable.

The aim of this project is to develop a computer based system, the Dynamic Lighting System (DLS), able to predict illuminances from both natural and artificial light, and the energy consumption of lighting systems combined with real control systems. The calculations will be performed at short time steps, using realistic sky models and real building geometry, to provide time-varying outputs of illuminances, electrical energy demand and the status of artificial lights.

Theoretical basis

The term daylight refers to light from the sky, excluding light from the sun. The *daylight coefficient* approach to calculating illuminance, is to divide the sky dome into a large number of patches, and treat each patch as a separate light source. A *daylight coefficient* is the fixed relationship between the luminance of a patch of sky and the resulting illuminance, both direct and indirect (figure 1), produced by that patch at a point of interest. The illuminance resulting from any sky can then be quickly determined by summing the luminance values of all the patches, scaled by the corresponding coefficients. The accuracy of predictions can be improved by dividing *daylight coefficients* into two components [2][3]: one is for the light arriving at a point directly from a sky patch, the *direct daylight*

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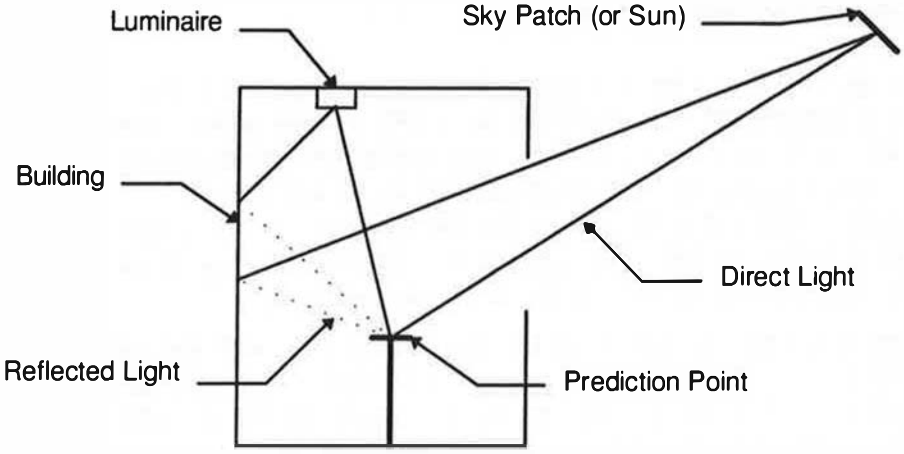

Figure 1 - Sources of illumination

coefficient; and the other is the coefficient for the light which arrives at a point after inter-reflection, the *indirect daylight coefficient*.

The DLS uses an advanced physically-based ray-tracing program, RADIANCE [4], to predict illuminance. RADIANCE was chosen because it is capable of calculating complex inter-reflections, and places no theoretical limitation on the complexity of the building geometry. Previous research at De Montfort University has validated the numerical accuracy of RADIANCE, when used in its native mode, for calculating illuminance values under complete skies [5], and when it was used in a proof of concept study, to calculate *daylight coefficients* [3].

This research extends the *daylight coefficient* approach to predict illuminance due to the sun, using *sunlight coefficients*, and illuminance due to artificial lights, via *artificial light coefficients*.

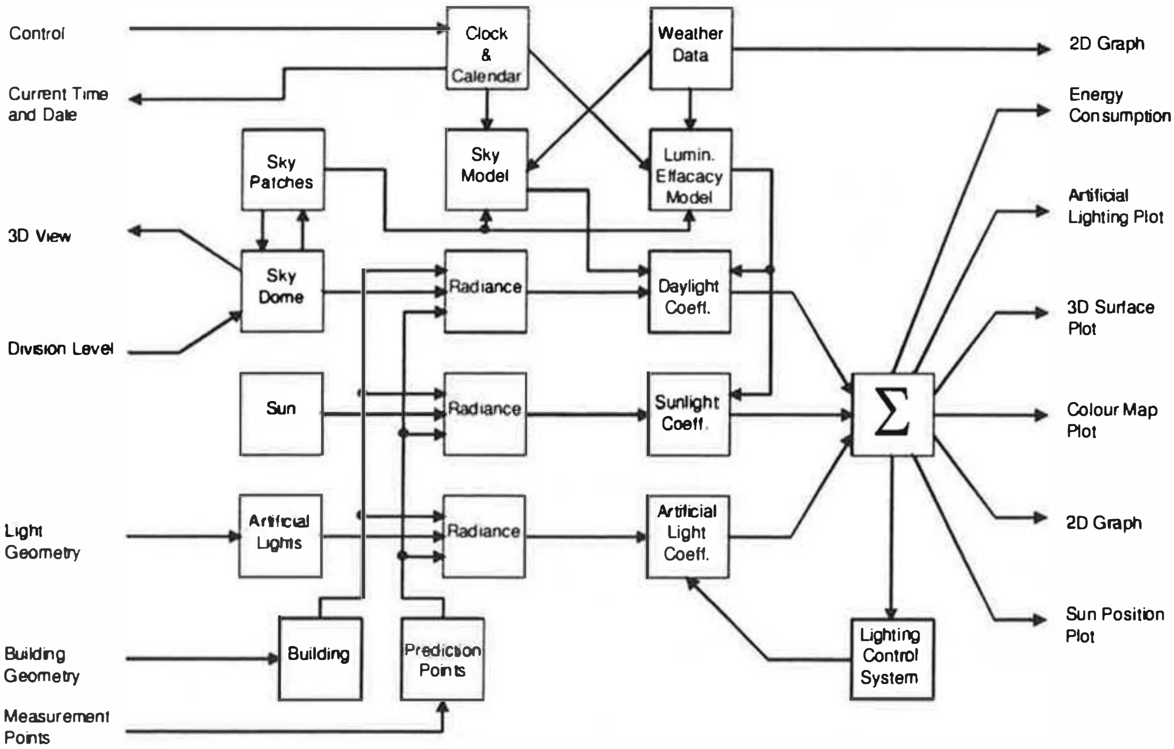

Figure 2 - DLS system diagram

The Dynamic Lighting System

The DLS program (figure 2) has two distinct functions: (i) to generate coefficients; and (ii) to use those coefficients to evaluate the performance of the lighting scheme under consideration. The first function uses RADIANCE to calculate coefficients. This operation is performed only once for a given building geometry. The program's second function uses the coefficients to predict illuminances, by assigning the actual luminance values to each light source and summing the light arriving at each prediction point, after weighting by the pre-calculated coefficients. This function may be used repeatedly, i.e. at each time step of the calculation, without re-calculating the coefficients.

If alternative light switching algorithms are investigated, the same coefficients can be used. The *artificial light coefficients* must be re-calculated if different luminaire designs are specified, but this is relatively quick. Only if the building geometry changes do the *daylight coefficients* and *sunlight coefficients* need to be re-calculated.

Constructing a sky dome

The approach chosen was to divide the sky hemisphere into a series of spherical triangles, as illustrated in figure 3. Triangles were chosen because they are suitable for recursive sub-division, which allows the degree of discretisation to be varied. When using RADIANCE, distant light sources, i.e. sources with a small solid angle, are described by a direction vector and a cone angle. The cross-sectional shape of the source is therefore irrelevant. The triangular patches were used to supply a centre vector and a cone angle (equivalent to each triangle's solid angle), each patch being treated as a

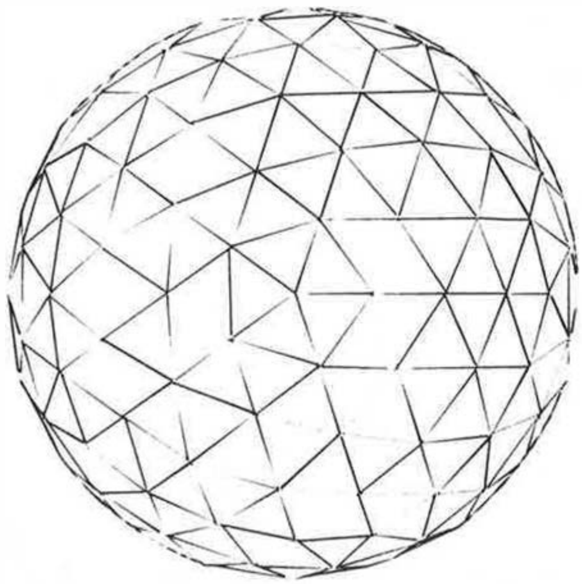

Figure 3 - A 160 Patch Sky Dome

separate light source.

Calculating coefficients

The description of each sky patch, which is given unit luminance, is combined with the building geometry, to calculate its *indirect daylight coefficients* using RADIANCE. *Indirect daylight coefficients* are derived in two stages. The scene is first simulated, to calculate an approximate coefficient for the total light, both direct and indirect (inter-reflected), arriving at a point. The simulation is then repeated to calculate an approximate coefficient for the direct component only. This direct coefficient is then subtracted from the total value to leave an accurate value for the *indirect daylight coefficient*. The process is repeated for each patch / prediction point combination.

Direct daylight coefficients are predicted, using direct sampling. The scene is simulated with a complete hemispherical sky dome, and single rays sent from each prediction point towards the centre of each sky patch. The resulting values will be either zero, if the ray hits part of the building, or the sky luminance value (attenuated by any participating media such as glass), if the ray hit the sky dome. This method of calculating the *direct daylight coefficients* is both fast, as it requires only a single RADIANCE simulation, and accurate, as it allows a higher level of discretisation to be used.

The coefficient approach can be used to model light from the sun. Due to the potentially very high luminance of the sun, and the small angle it subtends, an error in the position of the sun when calculating its coefficients, can cause large errors in illuminance prediction. This could be avoided by calculating *sunlight coefficients* for every sun position, but this could yield a very large number of coefficients. If a high level of sky dome discretisation is used to calculate *direct daylight coefficients*, the nearest *direct daylight coefficient* can be used for the *direct sunlight coefficient*. Similarly, the nearest *indirect daylight coefficient* can be used for the *indirect sunlight coefficient*. This method accepts a small sun position error, in exchange for greater flexibility of the software

The coefficient approach will be used to predict illumination from artificial lights. A definition of each luminaire, which can include complex distribution patterns, will be used as the luminance source. This aspect of the project has not yet begun.

Using coefficients

The internal illuminance at each point due to daylight is found by assigning realistic luminance values to each sky patch, scaling those luminance values using the corresponding *daylight coefficients*, and summing the resulting illuminances. The luminance values for each sky patch are predicted using a *sky model*, such as the Perez All-Weather Model [6]. The Perez model, like many others, uses values from locally measured *weather data*, diffuse horizontal irradiance and direct normal irradiance, along with the sun position, to produce a luminance distribution pattern, similar to the distribution of the real sky. A *luminance efficacy model* is used to convert diffuse horizontal irradiance in the *weather data*, to diffuse horizontal illuminance, used to scale total illuminance from the *sky model* to match the real sky.

The illuminance due to sunlight is found by scaling the sunlight luminance using the *sunlight coefficients.* The sun's luminance is obtained from direct normal irradiance, which is converted to illuminance, also using a *luminance efficacy model.*

The illuminance due to artificial lights will be found by scaling the luminance of the luminaires using the *artificial light coefficients.* The total light output of individual luminaires, may be determined by the feed-back from the lighting control system. Control may be manual or by photo-cell, leading to simple on / off switching or dimming. As the calculations proceed, the length of time the luminaires are active will be recorded, enabling the total energy consumption to be calculated.

Target computer platform

The RADIANCE programs are written in C, and are primarily designed to run under the UNIX operating system. UNIX workstations are currently thought to provide the best environment for performing the computationally intensive RADIANCE calculations. The initial target platform for the DLS is therefore a UNIX workstation, although with the exception of the RADIANCE modules, the DLS is designed to be platform independent.

The programming language chosen for developing the DLS is Java [7]. Java programs can provide a common Graphical User Interface, running on any platform which provides a Java Virtual Machine, e.g. UNIX, PC or Apple Macintosh. Java provides extensive network features that would allow the DLS to be constructed in a Client / Server configuration, permitting coefficient calculation and data analysis to be performed on different systems.

The DLS is designed so that it can be extended easily. The Object-Oriented nature of Java encourages a highly modular design, features such as Interface Specifications allow new modules to be added, e.g. alternative sky models, without the programmer having to understand the whole system.

Validation

The illuminances predicted by the DLS, for natural light only, using the Perez All-Weather [6] *sky model*, have been compared with equivalent predictions, produced by RADIANCE operating in its native mode. Previous validation studies by Mardaljevic [3][5], have confirmed the accuracy of RADIANCE by comparing predictions with illuminance measurements made in a typical office. The same test room was used for this inter-model comparison.

The deep-plan test room (9m deep, 3m wide and 2.7m high), was lit by daylight and sunlight from a window of plain glass located at one end. Illuminances were predicted for a row of points, at working plane height (0.7m), spaced along the centre line of the room.

As an illustration, the predicted illuminances at a point 1m from the window, are compared with the predictions produced by native RADIANCE in figure 4. Each data point is for one sky condition. These were defined from diffuse horizontal irradiance and direct normal irradiance, measure in the UK during 1992. The 710 data points represent a wide range of sky conditions. Sky conditions, for which there is not a valid equivalent Perez *sky model* distribution, have been excluded. DLS simulations were

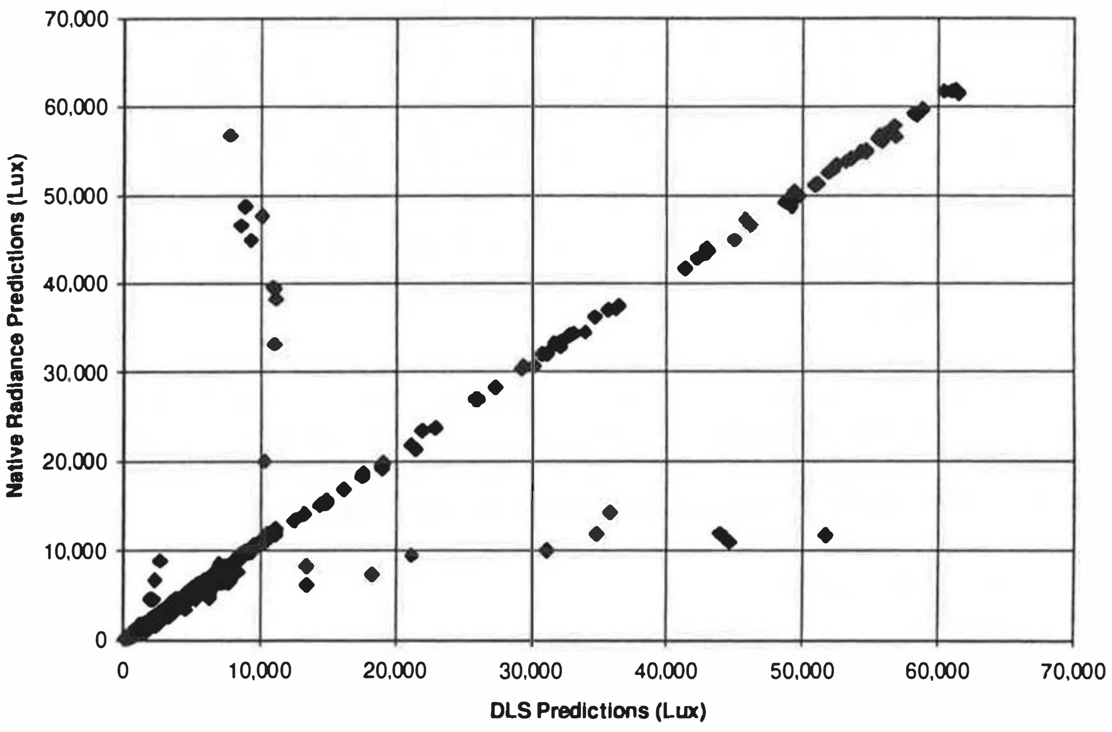

Figure 4 - Comparison of illuminance predictions

performed using a sky dome discretisation of 640 patches, for *indirect daylight coefficients*, and 2560 patches for *direct daylight coefficients.*

It can be seen that although the predictions produced by the two methods compare reasonably well in most cases, there are a few instances where the values are significantly different. These occur when small imperfections in the sun's placement causes it to be visible to the prediction point (in the DLS), when it is actually hidden (in native RADIANCE), and visa versa.

Conclusions

A Dynamic Lighting System has been produced that predicts internal illuminance.

- It has been shown so far that the DLS is capable of accurately predicting internal illuminances from natural light, under a wide range of sky conditions.
- The DLS program, written using Java, will run on a PC, Apple Macintosh or UNIX workstation.
- When the project is completed it will be possible, for the first time, to quantify the electrical demand of lights in any space, with any lighting control strategy, when combined with natural light delivered by an innovative glazing systems.

Work is currently in progress to extend the coefficient approach to include artificial lights and lighting control systems.

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References

[1] Tragenza, P.R., Waters, I.M., "Daylight coefficients", *Lighting Res. Technol.* **15**(2), pp. 65-71, 1983.

[2] Littlefair, P.J., "Daylight coefficients for practical computation of internal illuminances", *Lighting Res. Technol.* **24**(3), pp. 127-135, 1992.

[3] Mardaljevic, J., "Daylight coefficients for Illuminance Prediction: Formulation for Lighting Simulation Program and Validation", (Submitted to) *Lighting Res. Technol.*, 1997.

[4] Ward, G.J., "The RADIANCE lighting simulation and rendering system", *Computer Graphics, Proceedings, Annual Conference Series*, pp. 459-472, 1994.

[5] Mardaljevic, J., "Validation of a lighting simulation program under real sky conditions", *Lighting Res. Technol.* **27**(4), pp. 181-188, 1995.

[6] Perez, R., Seals, R., Michalsky, J., "All-weather model for sky luminance distribution - preliminary configuration and validation", *Solar Energy* **50**(3), pp. 235-245, 1993.

[7] Halfhill, T.R., "TODAY the WEB, TOMORROW the WORLD", *Byte*, pp. 68-80, January 1997.

The use of dynamic and diffusive insulation for combined heat recovery and ventilation in buildings

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Introduction

Modern buildings, domestic and commercial, have attempted to reduce their energy requirements by improving the airtightness of the envelope and increasing the thickness of insulation. However, this trend has developed simultaneously with increased use of synthetic materials in construction, furnishings and decorations, which give off volatile organic compounds, and increasing living standards which result in higher indoor temperature and moisture generation rates within homes. The result has been a reduction in indoor air quality which directly affects occupant health and increasing problems of dampness in homes, particularly for the poor.

Dynamic and diffusive insulation, which permit the movement of air, moisture, etc., through the external walls of a building, were seen as two potentially complementary methods for reducing ventilation and building envelope heat losses and achieving high indoor air quality. Dynamic insulation is also known as "pore ventilation" which is a more accurate description of the technology. A dynamically insulated envelope is constructed using air permeable materials so that air is able to flow through the wall driven by a pressure difference between inside and out created by fans or stack effect. The distinguishing feature between dynamic and diffusive insulation envelopes is that the former has neither an air barrier nor a vapour retarder whereas the latter is any construction without a vapour barrier.

The EPSRC funded research project was set up in January 1995, to provide a firm scientific understanding of dynamic and diffusive insulation. An important outcome of the research will be the development of building envelope designs which effectively and economically employ dynamic insulation in UK climatic conditions, without detriment to existing UK building practice and standards.

A theoretical understanding of heat, air and moisture transfer, which has been empirically verified, has been achieved. The resulting model has been used to study the energy and air flow balance within a dynamically insulated home, enabling general conclusions to be drawn about the effectiveness of this form of construction. The paper outlines the key theoretical and empirical results which will permit a designer to explore the potential for using dynamic and diffusive insulation in any proposed building.

Although work is still in progress, some general conclusions about dynamic and diffusive insulation will be presented. The results to date indicate that the energy saving produced by dynamic insulation alone is small in comparison with that obtained using conventional ventilation air heat recovery methods. The two can however be cumulatively combined to produce additional savings. Contrary to popular belief, our study of diffusive insulation suggests that it does not offer the possibility of significant improvements in air quality.

Dynamic and diffusive insulation

Heat Transfer

Physical insight into the heat and mass transfer processes in dynamic and diffusive insulation for any proposed envelope design can be gained from a simple 1-D analytical model. The model can be used to predict the effective or dynamic U-value for the envelope and the mass transport rate for any gas

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species. The dynamic U-value can be incorporated into an energy and air flow balance for the whole building to estimate the overall energy savings. This simple analysis which can be carried out on a spreadsheet is ideal for the conceptual design of buildings. However, for the design of the air permeable envelope details, 2-D models of the heat air and moisture transport should be used to assess (i) air bypassing the insulation through defects or construction details, (ii) buoyancy effects in the porous insulation, defects and cavities, and (iii) increased heat losses and vapour transport due to the above.

There are a number of such models in existence but they tend to be research tools and not available for use by practitioners. Hens [1] provides an excellent review of heat air and moisture transport modelling in general and specific computer programs in particular.

This paper will describe the practical results of the 1-D analytical model. Taylor, Cawthorne and Imbabi [2] showed that the dynamic U-value for a multi-layer envelope can readily be calculated from the total thermal resistance of the wall (R_s) and the air flow through the wall (v)

$$U_d = \frac{v \rho_a c_a}{R_s(\exp(v \rho_a c_a R_s) - 1)} \qquad 1$$

The dimensionless group of variables that controls the behaviour of dynamic insulation has a formal resemblance to the Péclet number

$$Pe = \frac{v \rho_a c_a L}{k} \qquad 2$$

Unlike boundary layer analysis where it is the fluid physical properties that are employed, the thermal conductivity, k, in this case refers to the porous material. The density, ρ_a, and specific heat, c_a are that of the air.

Table 1 illustrates how the material thermal conductivity and the air flow combine to determine the dynamic U-value for two envelopes, one comprising 200 mm of cellulose insulation and the other 200 mm thick porous masonry block such as Pumalite. The masonry wall requires an air flow approximately ten times that of cellulose to achieve a comparable improvement (U_d/U_s) in U-value. However, to achieve the same insulation value the air flow through a Pumalite wall would have to be about 100 times that for cellulose. Consideration of the pressure drop across the wall (280 Pa) at a flow rate of 100 m/h leads to the conclusion that it is not a practical proposition. Thus dynamic insulation works best with materials that are inherently good insulators. However, the thermal capacity of the masonry can be combined with the insulating properties of the cellulose to produce a composite permeable wall with a low U-value and high thermal capacity.

Table 1: Dynamic U-Value versus thermal conductivity and air flow rate

	Cellulose (k = 0.035 W/mK)		Pumalite (k = 0.3 W/mK)	
v (m/hr)	1	10	1	10
Pe	1.91	19.1	0.224	2.24
U_d / U_s	0.33	9.5 E-8	0.89	0.27
U_d (W/m^{2}K)	0.058	1.7 E-8	1.34	0.4

Another reason why this is the case is that the analytical theory assumes that the air and the solid matrix of the porous insulation are in local thermal equilibrium. This assumption is valid for low air flows. Calculating the air flow at which the equilibrium theory is not applicable in terms of the physical properties of the porous medium is one of the useful results to be obtained from a non-equilibrium theory of dynamic insulation which is under development. It is sometimes suggested that with dynamic insulation less insulation material may be used in the wall. From Table 2 it can be seen that to get a significant reduction in U-value for a wall with only 40 mm of insulation high air flows are again required.

Table 2: Dynamic U-Value versus insulation thickness

	Cellulose (L= 200 mm)		Cellulose (L= 40 mm)	
v (m/hr)	1	10	1	10
Pe	1.91	19.1	0.382	3.82
U_d / U_s	0.33	9.5 E-8	0.82	0.085
U_d (W/m^{2}K)	0.058	1.7 E-8	1.23	0.13

Another feature of dynamic insulation is that as the air flow increases the inner surface temperature decreases [3]. This is because more heat has to be put into the inner surface of the wall to heat the increasing amount of air which in turn increases the temperature drop across the air film thermal resistance. The temperature drop is about 0.5 ºC for a flow of 1 m/h through a wall with 200 mm of cellulose insulation increasing to over 5 ºC at 10 m/h. Even at low air flows this temperature depression will significantly alter the radiant heat exchange within a room.

Mass Transfer

Diffusive insulation is merely a special case of dynamic insulation where the air flow is zero. In other words its thermal behaviour is no different from a conventional wall. Indeed diffusive insulation is merely a wall which does not include a vapour retarder with a high vapour resistance such as polythene or metal foil. Such wall constructions are acceptable in certain circumstances and BS 5250 [4] quotes a useful but not infallible rule of thumb that the vapour resistance on the warm side of the insulation be at least five times greater than that on the cold side. It is claimed that diffusive insulation permits the diffusion outwards of indoor pollutants such as water vapour and volatile organic compounds. However, diffusion, even without a vapour barrier, is such a slow process that water vapour is transported much more quickly through the wall by air flowing through cracks and crevices. Diffusion can be stopped if the air is flowing in the opposite direction to the diffusion process. The critical air velocity v_c required to do this is dependent only on the ratio of the concentrations of the gas (inner concentration C_i assumed to be greater than the outer concentration C_o) and the total diffusion resistance of the multi-layer wall R_d[2]:

$$v_c = \frac{\ln\left(C_i / C_o\right)}{R_d} \qquad 3$$

This explains how dynamic insulation can act as a vapour barrier. If the air velocity is greater than v_c then water vapour will be carried from outside to inside despite there being a higher water vapour concentration on the inside. For a typical timber frame insulated wall construction with total thermal resistance of 6.434 m^{2}K/W (200 mm cellulose insulation) and the indoor and outdoor temperature and humidity conditions of 15 °C, 85% RH and 5 °C, 95% RH respectively as specified in BS 5250, this critical air velocity is very low at 0.0063 m^3/m^{2}h. This is very much lower than the air flows of 0.5 to 1.5 m^3/m^{2}h recommended by Dalehaug [5]. The partial vapour pressure difference corresponding to the standard internal and external conditions, stated above, is 621 Pa. The authors have measured the air permeability of a variety of insulating materials and the air permeance of 200 mm of cellulose is found to be 1.5 m^3/m^{2}hPa. and that for 12 mm thick softboard was 0.116 m^3/m^{2}hPa (Appendix 1). The controlling resistance to air flow in a wall construction comprising of wood wool board (air permeance too high to measure), 200 mm cellulose, 12 mm softboard is the softboard. The pressure drop across the wall at the critical air flow corresponds to a difference in air pressure of only 0.054 Pa Thus water vapour cannot flow from inside to out through a wall operating in contra-flux (heat and mass flow in opposite direction) mode.

There is then a conflict between the air flow requirements to minimise heat losses and that necessary to maximise the removal of water vapour or other indoor pollutants. On the other hand provided one can ensure that air is flowing inwards through the envelope at all time then there should, in general, be no problem of interstitial condensation. However, if the outer wall cladding is saturated by wind-driven rain followed by heating by the sun then the temperature and relative humidity in the cavity could rise very quickly and condensation could occur in the still relatively cool insulation.

One of the most useful outcomes of the recently completed IEA Annex 24 on heat air and moisture (HAM) transport in buildings has been the compilation by Kumaran [6] of data on air permeability, water vapour permeability and hygroscopicity for many building materials.

Systems analysis

Equation (1) can be readily incorporated into an air flow and energy balance for a whole house to calculate the heat loss through the air permeable parts of the envelope [7]. A fact that is often overlooked by the proponents of dynamic insulation is that whilst the heat loss to the outside is reduced more heat needs to be put into the interior surface of the wall in order to warm the incoming air than would be the case without air flow. Therefore, if the air coming through the wall is merely vented to atmosphere without heat recovery little is gained. With an air-to-air heat recovery scheme as shown in Figure 1 the ventilation requirements are supplied partially through the wall, m_p, and partially through the heat exchanger, m_f. The model also allows for air leakage through doors and windows, m_l. The heat input to the building Q (partly supplied by incidental gains) compensates for the heat lost through the porous envelope Q_p, the non-porous part of the envelope, Q_n and the ventilation loss.

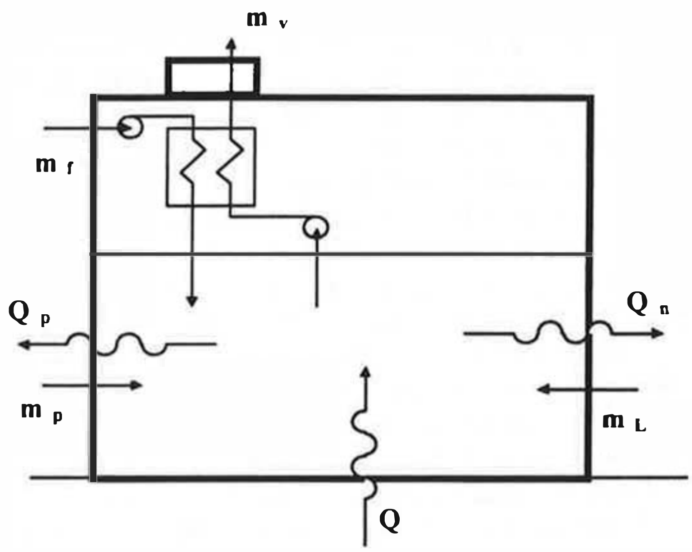

Figure 1: Dynamic insulation with air to air heat recovery

The only way a building can be reliably depressurised in the mild and variable UK cilmate is by using fans. In northern Scandinavia with a 40 °C temperature difference between indoors and out in winter a reliable and significant stack affect may be obtained. The depressurisation must be no greater than 5 to 10 Pa otherwise the occupants will have difficulty opening doors and windows [4]. This restriction on depressurisation could be relaxed if the opening and closing of windows and doors were mechanically assisted. Since the pressure drop through an air-to-air heat exchanger and associated ductwork is in the region of 50 to 100 Pa both a supply and an extract fan are required.

The results of analysis of such a scheme are shown in Figure 2. The ordinate plots the reduction in energy consumption over a conventional envelope construction of the same static U-value for the same air change rate to maintain an indoor temperature of 20 °C when it is 0 °C outside. The curves show how a dynamically insulated building and conventional envelope compare when both use air-to-air heat recovery. At low air change rates the conventional building performs better than the dynamically insulated building. The bigger and better the heat exchanger the higher is the air change rate before it becomes worth while to think about dynamic insulation. Both schemes show a maximum saving at around 1.5 to 2 ach. This level of ventilation in a conventional house could be achieved merely by opening the windows.

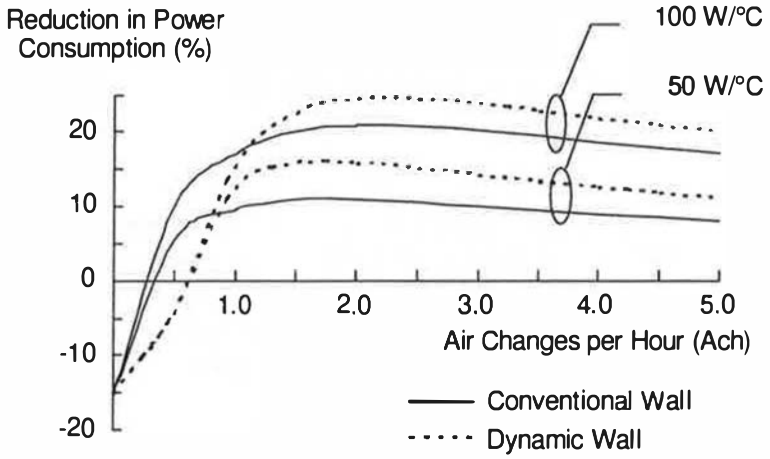

Figure 2: Heat recovery with conventional and dynamic envelopes

An air-to-water heat exchanger operating at 2.0 ach would require a continuous steady flow of water of the order of 1550 kg/day in a home. This flow rate is much larger than the domestic requirements for bathing, showering, laundering also the temperature constraints imposed by the exhaust air flow and the heat exchanger mean the water temperature will rise only from about 5 °C to 15 °C. If the warm air were used instead to melt snow the water it would provide at, say, 10 ºC is a more manageable 170 kg/day. However, snow is not a reliable heat sink in most areas of the UK.

With the simple tools developed so far the designer can explore, for example, how the proportion of non-permeable surfaces (such as glazing) to permeable surfaces and how the size of the building affect thermal performance. The results are much as one might expect. To make the most effective use of dynamic insulation as great a proportion of the external envelope as is practical should be air permeable. This has obvious implications for the use of incident solar radiation for lighting and heating. It also means that a detached house is a more suitable candidate for dynamic insulation than a small apartment with only one or at most two external surfaces. As the volume of the building increases, the ratio of volume to surface area increases and so the relative importance of the ventilation heat loss to envelope loss increases. In general, where energy conservation is the main objective, dynamic insulation would appear to be appropriate only for small detached buildings.

Indoor air quality

A porous wall will inherently act as a filter. Studies of porous ceilings in barns where the ventilation rate can be as high as 80 m^3/m^2h have shown that over a span of 20 years the pressure increase due to dust accumulating in mineral wool insulation is insignificant [8]. This may be due in part to the relatively low density (15 kg/m^3) of the insulation. In homes, the ventilation rate will be an order of magnitude smaller and the rate of dust accumulation in the walls will be correspondingly slower. The authors are not aware of any data on the filtration efficiency of cellulose insulation as a function of particle size. Insulation materials such as cellulose and mineral wool will not remove chemical pollutants in the way that activated charcoal filters would.

Cellulose insulation fibre is treated with borax to prevent fungal growth and infestation by insects and rodents. Bacteria cannot survive in the air on their own: they require dust particles to sustain small colonies. When these dust particles are trapped in the insulation, bacteria living on them may multiply unaffected by the borax in the cellulose. The microbes and or toxins they may produce may then subsequently be disseminated into the living space. The bacteria may provide the nutrients required by moulds and fungi to grow [9]. This potential health hazard requires investigation in order to identify the circumstances under which dynamic insulation may act as an amplifier and disseminator for bacteria, fungal spores and viruses.

In view of the risks attached to mechanical ventilation systems, which may be overcome by proper maintenance, the hybrid scheme (Fig 2) offers no health advantages over a purely mechanical ventilation system. An air to water heat exchange system might be better in this respect.

With contaminants released within the building such as volatile organic compounds (VOC's), body odours, cooking smells, spores from moulds these are best dealt with by extracting them at source and venting directly to outside. Dynamic insulation might be able to contribute to their dilution and removal by permitting higher ventilation rates or preventing their spread by plug flow of fresh air from a wall or ceiling. Diffusive insulation will not reduce the concentrations of these substances in the indoor air rapidly enough to be of any practical use.

Future for dynamic and diffusive insulation

Diffusive insulation is not a practical method of ventilating a building designed for human activities. In contrast, it has been shown that dynamic insulation will, as has been claimed, cut down on the conductive heat loss through the wall. Dynamic insulation, operating in contra-flux mode, will also prevent water vapour getting into the wall from the interior. This had not previously been fully appreciated. However these benefits are not easy to achieve in practice:

- the rest of the building needs to be exceptionally air tight and air flow through the walls needs to be reasonably uniform
- difficult to ensure air flows inward through the wall under all internal and external climate conditions
- under certain conditions (e.g. sun shining on wet timber cladding) one may get interstitial condensation with air flowing inwards
- energy must be recovered from the ventilation air
- the building occupants need to understand how the building works and to behave accordingly.

In short, the design effort and quality control during manufacture and erection of a dynamically insulated building is greater than that required for a building with conventional air tight, well insulated envelopes in order to ensure acceptable hygro-thermal performance.

In the concluding stages of this project the thermal performance of an air-to-air heat exchanger with fans which are continuously and independently variable is being measured. The fans in commercially available air-to-air heat exchangers are electrically linked to provide step changes in air flow so that the exhaust flow is always about 10% greater than the supply flow. This data will provide greater confidence in the estimation of the heat recovered from the vented air and provide guidance on how best to couple dynamic insulation with ventilation heat recovery. Whilst the simple 1-D theory based on thermal equilibrium has been proven to be adequate for the air flow rates through the envelopes of houses it is quite likely at the high flow rates associated with porous ceilings in sports halls and swimming pools (greater than 20 m/h) a non-equilibrium theory is required.

Future research on dynamic insulation will need to focus on developing designs that are (a) safe for humans, (b) durable and (c) cost effective. In particular, when insulation materials are used as pore ventilation, a very effective disseminator, the safe assumption is to assume that some microbes will find that environment adequate to support a growing population. Research should be directed to finding which microbes will multiply and the environmental conditions that favour this growth.

Acknowledgements

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References

[1] Hens, H., 1996, IEA-Annex 24 on Heat, Air and Moisture Transport in Highly Insulated Envelopes, *Final Report Vol 1 Task 1: Modelling*, Leuven.

[2] Taylor, B. J., Cawthorne, D. A., Imbabi, M. S., 1996, *Analytical Investigation of the Steady-State Behaviour of Dynamic and Diffusive Envelopes*, Building and Environment, **31**, pp 519-525.

[3] Taylor, B. J., Imbabi, M. S., 1997, *The Effect of Air Film Resistance on the Behaviour of Dynamic Insulation* (In preparation)

[4] BS 5250:1989, *Control of Condensation in Buildings*, British Standards Institution, London.

[5] Dalehaug, A., 1993, *Porous Insulation in Walls,* Research Report No 53, Hokkaido Prefectural Cold Region Housing and Urban Research Institute.

[6] Kumaran, M K., 1996, IEA-Annex 24 on Heat, Air and Moisture Transport in Highly Insulated Envelopes, *Final Report Vol 3 Task 3: Material Properties*, Leuven.

[7] Taylor, B. J., Imbabi, M. S., 1996, *Dynamic Insulation - A Systems Approach*, 4th, Symposium Building Physics in the Nordic Countries, Vol 2., Espoo, Finland, 9-10 September.

[8] Sällvik, K., 1988, *The Influence of Clogging on the Air Penetrability in Porous Materials used for Air Inlets*, International Symposium on Porous Ceilings, 18 to 19 Oct 1988, Bundesanstalt fur Alpenländische Landwirtschaft, Gumpenstein, Irdning, Austria.

[9] Singh, J. ed., 1994., *Building Mycology: Management of Decay and Health in Buildings*, E & F N Spon, London.

Appendix 1: Measured air permeability of building materials

Material	Permeability (m^2/hPa)	Component	Permeance (m^3/m^2hPa)	Pressure Drop (Pa) [1]
Plasterboard	1.06×10^{-5}	12 mm sheet	8.81×10^{-4}	1140
Thermal block (density 850 kg/m3)	1.6×10^{-5}	100 mm block	1.9×10^{-4}	526
Fibreboard	1.34×10^{-3}	12 mm sheet	1.16×10^{-1}	8.6
Pumalite (density 870 kg/m3)	3.6×10^{-2}	100 mm block	3.6×10^{-1}	2.8
Cellulose / wet blown (density 47 kg/m3)	0.283	200 mm	1.50	0.67
Cellulose / dry blown (density 65 kg/m3)	0.25	150mm	1.67	0.60
Sheep's wool (density 28kg/m3)	1.8	140 mm	13.0	0.08

(1) Pressure drop calculated at flow rate of 1 m^3/m^2h

Modelling temperature and human behaviour in buildings 2) Thermal comfort field studies: 1996-1997

Fergus Nicol and Kate McCartney, Oxford Brookes University[1]

Summary

A year-long survey of thermal comfort is described following the methodology of the first part of this paper. The aim of the survey is twofold:

- to improve and perfect the adaptive algorithm described in the first paper
- to show how other environmental and social factors impinge on the adaptive algorithm and to suggest ways in which these can be incorporated in to it.

The philosophy and form of the survey is described.

Introduction

Work at Oxford Brookes University which is receiving support from the EPSRC (*Human thermal comfort and the formulation of temperature standards in buildings ref GR/K80280*) and the DoE (through an EnREI fellowship) is aimed at producing a dynamic standard for indoor temperatures in the form of a real-time algorithm for comfort temperature in terms of outdoor temperature

There are two distinct objectives to the current field studies:

Firstly, it is intended to establishment the relationship between external temperature and internal comfort temperature in naturally ventilated buildings, this relationship having first been suggested by Humphreys (1978) and further developed from analysis of the pilot study (Humphreys and Nicol, 1995). An adaptive algorithm exists from which target internal temperatures can be specified and it is this algorithm which requires verification and fine tuning. The data gathered from the field studies should give a more accurate picture of building performance and occupant preferences than data gathered from more laboratory based experiments. This part of the research is supported by the Engineering and Physical Sciences Research Council.

The second objective of the research is to extend the adaptive algorithm to account for subjective responses to physiological and psychological stimuli. Until recently, thermal comfort studies have concentrated mainly on easily measurable, physical factors, such as temperature, air velocity and humidity. Whilst some studies have also considered the other factors such as lighting, noise, job satisfaction, job autonomy and health, they have seldom looked at all these factors together and have not investigated the interactions between them. The field studies being undertaken for this research cover a wider range of issues than normal, and it is hoped to develop the adaptive algorithm to include their effects. This part of the research is supported by the Building Research Establishment as part of their EnREI programme.

The field studies

The design of the experiment is based on the pilot study described in the first part of this paper (Nicol and Raja 1996) which is part of an international series of experiments which have also taken place in

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Pakistan (Nicol et al 1994, Nicol, Raja and Alauddin 1997), are currently taking place in Tunisia and are planned for South America, Malta and Central Africa.

The basic design is of simultaneous transverse and longitudinal surveys. The longitudinal surveys, in which a subjects respond to a questionnaire four times each working day, creates a database from which the time-variation of comfort conditions can be followed. The transverse surveys are carried out once a month for a complete year using a much larger population of subjects and including their reactions to other environmental variables and wider physical measurements. They fulfil two roles:

- they generalise the results of the longitudinal survey to a larger population
- they allow the influence of other environmental variables on the adaptive algorithm to be assessed

16 buildings are being monitored for 12 months, involving some 800 individuals. The buildings are a mixture of heavyweight and lightweight construction, and naturally ventilated and air conditioned. 6 of the buildings are situated in Aberdeen, whilst the remaining 10 are situated in and around Oxford. The field studies themselves consist of 2 parts: the transverse survey and the longitudinal survey. A longer background questionnaire was also sent to each project participant, and this is discussed below.

The transverse survey

The transverse study involves each project participant answering a short questionnaire which is administered at their desks each month. Measurements of air temperature, globe temperature, air velocity, relative humidity, lighting level and finger end temperature are taken at the time of the questionnaire, either using a datalogging device or hand held instruments. Each question requires the occupant to rate how they feel about a particular aspect of their environment at that time, on a 7-point scale, and then asks them to indicate a preferred environment on a 5-point scale. Question 1 from the transverse questionnaire is shown below:

How do you feel at this time?	**How would you prefer to feel?**
Cold	Much Warmer
Cool	A Bit Warmer
Slightly Cool	No Change
Neutral	A Bit Cooler
Slightly Warm	Much Cooler
Warm	
Hot	

Similar questions follow on air velocity, humidity, lighting level, noise level and overall comfort. The respondents are also asked to estimate the actual temperature of their internal environment. The questionnaire administrator notes down the respondents' clothing and what they have been doing in the previous hour. From these observations, a CLO (clothing insulation) value and MET (metabolic heat production) rate can be established. The use of environmental controls is also noted, e.g. window open or closed, heating on or off. From all this data, a very accurate assessment of a particular individual's response to their environment can be made. To date, approximately 80 transverse surveys have been carried out.

The longitudinal survey

The longitudinal survey involves around 10% of the project participants at any time. This smaller group is asked to complete a short checklist, 4 times a day. The checklist requires a feeling vote and preference vote on temperature only, with the respondents ticking appropriate boxes. A sample question is shown below:

At this time I feel *(please tick)* :	AM.......	AM.......	PM.......	PM.......
Much too warm				
Too warm				
Comfortably warm				
Comfortable				
Comfortably cool				
Too cool				
Much too cool				
I would prefer to be *(please tick)* :				
Much cooler				
A bit cooler				
No change				
A bit warmer				
Much warmer				

A datalogging device is left on the respondent's desk to monitor temperature, air velocity and humidity every 15 minutes, and the readings from this are correlated with the respondent's answers. To ensure a high rate of return on these checklists, the people involved are changed every 3 months or so. Over a 3 month period, each participant provides on average 200 responses.

The background questionnaire

Each project participant is also sent a longer background questionnaire which asks for general details on a wide variety of issues. The questionnaire is split into 7 sections as described below. Space is left at the end of each section for any additional comments.

Section 1 - Personal Details
This section requires the respondent to indicate their sex, age, weight and height. This information is necessary to allow a demographical interpretation of the results.

Section 2 - Job Details
This section requires the respondent to give various details about their job. They are asked for their job title and a general description of what the job entails; an indication of their typical working hours, how much of that time is spent doing sedentary office tasks and how much is spent at a VDU; how do they usually travel to work; How long have they worked for that particular company, in that particular building and at that particular desk location; a description of any dress code within the building. They are also asked to indicate on a 7-point rating scale how stressful they consider their job to be, how much they like their job and how much they like the social atmosphere at work. This form of 7-point rating scale is used throughout the questionnaire and en example is shown below.

How stressful would you say your job is? *(please circle a number below)*

Not at all stressful 1 2 3 4 5 6 7 Very stressful

Section 3 - Working Environment
This section mainly consists of rating scales like the one shown above. The respondents are asked to indicate their overall impressions of the temperature and indoor air quality of their environment in the summer and winter. They are also asked to indicate whether their home environment is generally warmer or cooler than their working environment. One of the questions is shown below.

Please circle the number which best represents you views

Summertime Indoor Temperature

Often too hot	1	2	3	4	5	6	7	Never too hot
Often too cold	1	2	3	4	5	6	7	Never too cold
Excellent	1	2	3	4	5	6	7	Poor

In the summer, how does your home compare to your working environment? *(Please tick)*

Generally warmer than work [ ]   Generally cooler than work [ ] No difference [ ]

Similar rating scales are used to assess the respondents' views on the office lighting (brightness, stability, evenness, glare, daylight availability, overall excellence) and background noise (intrusiveness). The respondents asked whether or not they can see out of a window, and whether they are ever bothered by noise from distracting conversations, equipment or traffic. These questions are answered by ticking appropriate boxes.

<u>Section 4 - Other Aspects of the Working Environment</u>
This section involves 7-point rating scales on issues such as cleanliness, office decor, furnishings, layout and overall working conditions. The respondents are also asked to rate the importance on a scale of 1 to 7 of various aspects of their working environment, e.g. a friendly atmosphere, good lighting conditions.

<u>Section 5 - Personal Control</u>
This section deals with whether or not the respondent has control over various aspects of their environment (e.g. the ability to open or close a window, local heating control), how often they use these controls, whether or not they notice a difference in their environment when they adjust a particular control, how quickly a change occurs and how important they consider control of a particular environmental feature to be. The questions are all answered by ticking appropriate boxes, and an example is given below:

For the following items, please indicate whether or not you have *personal control* over their adjustment.

			If YES, how often do you *actually* make adjustments?				
	No	**Yes**	**Often**	**Sometimes**	**Seldom**	**Never**	
Open or close a window	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Adjust curtains or blinds	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Open or close an internal door	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Open or close an external door	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Adjust a thermostat	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Adjust a local heater/ radiator	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Turn lighting on or off (your desk only)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Turn office lighting on or off	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Adjust office lighting level (dimmer)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Adjust office air-conditioning	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Adjust a local fan/ air outlet	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

The respondents are also asked if they know what to do if they cannot control a particular environmental feature and require a change.

Section 6 - Health

The respondents are asked of they suffer from asthma, hayfever, eczema or migraines as these are some of the more common complaints associated with a poor office environment. They are asked if they wear contact lenses and if lens discomfort is increased whilst at work, a common sign of poor humidity. They are asked of they smoke or if people in their immediate vicinity smoke.

The Department of Human Sciences at Loughborough University are currently researching thermal comfort effects on people with disabilities or chronic health conditions. This questionnaire asks the respondents to indicate whether or not they are registered disabled or suffer from a chronic health condition, and whether or not they take any regular medication. Any information gathered from this part of the questionnaire will be shared with researchers at Loughborough.

Finally, the respondents are asked to indicate on a 7-point scale their perceived sensitivity to environmental conditions.

Section 7 - Concluding Comments

This section is left blank for the respondents to include any further comments or observations which they feel may be important. Many previous studies have gained much from such anecdotal data.

Data analysis

The data will be analysed using a number of multi-variable statistical techniques, e.g. regression analysis, probit analysis, multi-variant analysis. Software such as Microsoft Excel and SPSS are being extensively utilised. Due to the shear amount of data, some preliminary analysis will be done on a short fixed period before the final analysis is done on the whole data set. Fuzzy logic and reasoning is being investigated as a possible analysis technique.

The transverse and longitudinal surveys are running between March 1996 and September 1997, with the final results expected in early 1998. The background questionnaires were distributed in November 1996 and are expected back by the end of January 1997. The preliminary analysis on a small section of the data should be completed by summer 1997.

References

Humphreys M.A. 1978: Outdoor temperatures and comfort indoors, *Building Res. and Practice, 6 (2).*

Humphreys M and Nicol JF 1995: An adaptive guideline for UK office temperatures, in *Standards for thermal comfort, indoor air temperature standards for the 21st century (eds Nicol, Humphreys, Sykes and Roaf)*, E and FN Spon, London.

Nicol JF, Jamy GN, Sykes O, Humphreys MA, Roaf S and Hancock M 1994: *A survey of thermal comfort in Pakistan, toward new indoor temperature standards.* School of Architecture, Oxford Brookes University.

Nicol JF and Raja IA 1996: *Thermal comfort, time and posture* Oxford Brookes University.

Nicol JF, Raja IA and Alauddin, A 1997: *A survey of thermal comfort in Pakistan II, toward new indoor temperature standards*. School of Architecture, Oxford Brookes University (in press).

Identifying the environmental potential of 'smart' metering technologies: mapping home systems for sustainable futures

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Summary

This paper reports upon on-going research into the relationship between smart metering and sustainability funded by the Engineering and Physical Sciences Research Council (EPSRC), under the sustainable cities programme. The aim of this research is to encourage commercial utilities and public regulators to consider how they could exploit the environmental potentials embedded within 'smart' metering technologies. The first stage in achieving this aim has been to unravel the priorities and practices of utility companies, regulatory bodies and meter manufacturers, through in-depth interviews[2] and reviews of literature. Preliminary analysis of this information has resulted in the creation of a model framework of different types of metering technology systems. We have then examined the environmental potential of different types of metering systems which have been developed by manufacturers, and which are representative of the models identified. This has helped us to develop an understanding of the likely role of future metering systems in contributing to energy efficiency strategies. This paper will present the preliminary results of this investigation, focusing on one type of model metering system, in order to both highlight further research directions and identify some of the emerging implications for environmental and technical policy guidance.

Introduction

The development and use of 'smart' metering technologies in the utilities sector is creating new opportunities for the efficient use of energy resources. Through a convergence between telecommunications, meters and electrical appliances, it is fast becoming possible for utility companies to reach "beyond the meter" in order to passively and actively manipulate the operation of heating and lighting systems and domestic machines, apparently heralding a new era of the 'smart' home. As the 'gateway' technology which provides the passageway to customer's homes, the meter is central to this convergence (Guy and Marvin, 1995). These 'smart' technologies may have profound implications for our understanding of the role of information and interactive control in influencing resource use and shaping the environmental profile of contemporary cities. By investigating how pathways of 'smarter' metering developments are emerging in the UK, the degree to which different types of metering solutions can contribute to meeting wider policies for sustainable energy use can be assessed.

The evolution of 'smarter' metering in the UK

The common view of the electricity meter is as a 'dumb' measurement device, a black box which is often hidden away under the stairs, and of little interest to the customer. Relationships between the utility company and the customer in this conventional scenario are simple, with information taken from the home by a manual meter reader to enable billing by the utility. However, this vision is no longer representative of new electricity metering developments. In the UK, the metering industry has moved on apace during the 1980s and 1990s and much more technically complex metering systems have now

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[2] *During the study interviews were undertaken with a number of representatives from Regional Electricity Companies, meter manufacturers and communications companies. These provide the source material for many of the quotes included in this paper.*

been developed. There has been a shift from the meter as a simple measurement device to the meter as one of the core components of extended utility control systems, as illustrated in Table 1.

Table 1: Principal components and capabilities of 'smarter' systems

Principal components of 'smarter' systems	Types of capabilities
Enhanced functionalities	A range of new/ improved applications, i.e. multiple tariffs, fraud detection, automatic meter reading, remote disconnection, load surveys, scheduled debt repayment, programmed control of appliances, value-added services (e.g. home security systems, energy management packages etc.)
Improved communications	To allow the two-way relay of information using a variety of media i.e. radio, cable and telephone networks, power lines to carry data as well as electricity, smart cards.
Increased data processing capabilities	Using central computer systems for detailed profiling of customer demand data, and linking these into other databases e.g. billing, GIS.
Improved information interfaces	To translate data into an accessible form i.e. enhanced displays for customers or detailed visual consumption data at the utility end.

The producer/user relationships represented by these 'smarter' systems are increasingly complex, with a variety of more dense and reciprocal 'dialogues' required between the utility company and different types of customers. This revolution in metering reflects a total rethink in the management systems of utilities in the post-privatised electricity industry, a changing utility environment which will have many uncertain economic, environmental and social outcomes.

Understanding environmental potentials of 'smarter' metering

One of the main objectives of such advanced metering and communications technologies has been to increase the efficiency of the electrical power system to specifically benefit the environment (Dorey, 1991). Essentially, 'smarter' metering, by facilitating a variety of voluntary and direct environmental management techniques, can make a significant contribution towards the goal of reducing the total energy use of households (Dauncey, 1990). In addition, peak time demands can be reduced to balance out load curves and help defer the need for new energy supply capacity, and supply network electrical losses can be quickly located (Redmond, 1994). Table 2 looks at the techniques which can be facilitated in 'smarter' meters to achieve these energy efficiency objectives. It is evident that advanced electronic metering systems can potentially provide the foundations for much more effective environmental management of energy resources. However, different types of metering systems have widely variable capabilities for achieving these energy efficiency objectives. Therefore, the key question is whether environmental potentials are being recognised and realised as an important criteria in the technical evolution of commercial metering systems in the UK.

Table 2: Summarising the environmental potentials of 'smarter' metering systems

Environmental Techniques	Role of the 'smarter' metering system
Load profiling	To collect detailed consumer information which can then be used to control customers demand via active or passive means: *'At the individual customer level a further understanding of how much electricity is used for what purposes, and when, is vital information for efficient energy management' (Allera and Sturges. 1996, p208).*
Information provision	Displaying information is a passive means of load control in which the metering display is used to send economic messages (e.g. consumption in £ terms) or environmental messages (e.g. CO^2 emissions of households) to customers to influence their consumption patterns: *'As consumers there are a hundred things we can do to save energy. What we are lacking is the feedback system that can tell us how we are doing and encourage us to do it better. The intelligent meter can provide this feedback' (Dauncey, 1990, p60)*

Tariffing	Another passive method of load control involves pre-programming the meter with flexible, multi-rate tariffs, thus sending an economic message to customers to alter consumption patterns: *'Flexible multi-rate tariffs which reflect the purchase cost of electricity at particular times of the day or throughout the year are a particularly effective means of passive load control and peak load avoidance' (Whiteman, 1996, p4)*
Load switching	Actively controlling usage patterns e.g. activating load switches remotely to connect/disconnect appliances on customers properties at particular times. Networks of household appliances can be linked with non-essential appliances being shed at peak times.
Network efficiency	Improved feedback on system behaviour is possible with irregularities e.g. electrical losses, being quickly identified and targeted for remedial action.

Social actors shaping developments

The implementation of 'smarter' metering technologies critically depends on the importance which metering 'actors' place upon different evaluation criteria. Environmental potentials of metering systems are merely one such criteria for consideration, and will be evaluated alongside social, economic, technical and institutional factors. Therefore, we need to understand where environmental potentials of metering fit into current debates over the most appropriate systems for implementation in the UK. This has been achieved by undertaking interviews with representatives from regulatory bodies, utility companies, meter manufacturers, communications providers and interest groups. Many different stories have transpired from these interviews and these have provided the foundations for unpacking the complex developments in metering and helped us to gain an invaluable insight into future trends.

A four model framework for electricity metering

One way of understanding the ways in which environmental potentials can be developed in metering systems is to consider how different types of technologies influence the contexts for producer or user action. In other words, what is it that the utility company or the domestic customer can use the metering system for which will promote energy saving action. The four distinct models of metering, shown in Figure 1, can be seen as useful 'windows' to investigate and clarify the opportunities and

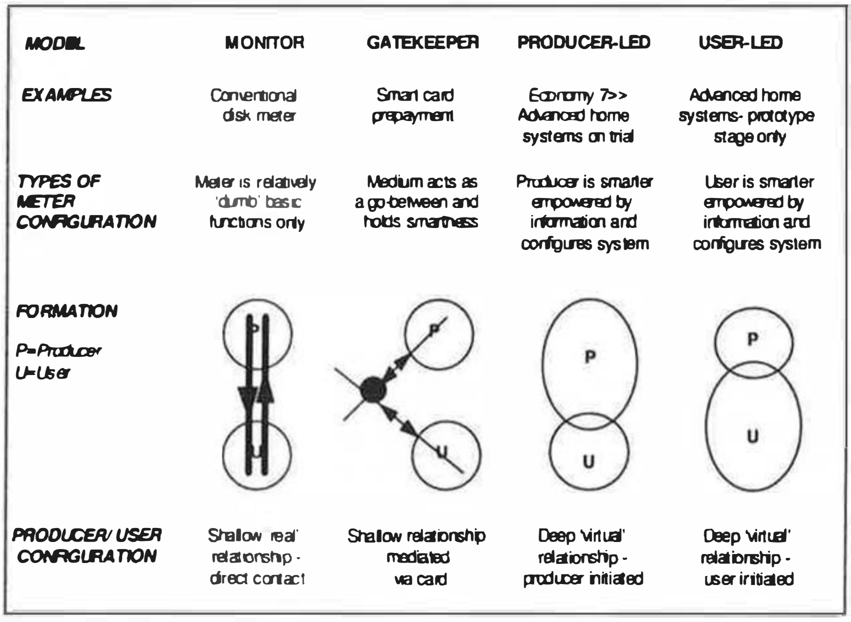

Figure 1: Conceptual model framework for electricity metering

constraints for environmental action inherent in different systems. By focusing on the meter, in each of these models, as the interface around which communications between the utility company and their customers are centred we can see that distinct sets of producer/user relationships are configured. By investigating these models, and the systems being developed by manufacturers which are representative of them, we can map out the potential for different home metering systems to enable energy saving action by producers and users.

In our *'monitor model'* the conventional view of the meter is depicted. This model reflects metering systems with basic functionalities and simple relationships between the producer and user, for example disk meters such as those present in the majority of UK households today. In the *'gatekeeper model'*, we see the introduction of a mediator into the system which is used to transfer information between producers and users. An example of this would be a smart card prepayment system where the card is used as the only way users can gain access to the system and subsequently resources. These systems have traditionally been used to replace coin prepayment meters and represent a solution to tampering and fraud, for a more limited domestic customer base. The *'producer-led model'* can be seen as a distinct shift towards the 'smarter' end of the metering spectrum. Earlier examples would include Economy 7 systems, but these have now been superseded by more advanced home metering systems, which represent the cutting edge of metering innovation, and are largely at trial stage in the UK. The producer can be seen to have a greater "footprint of influence" over the system relative to the user, i.e. their influence in directing the different uses to which the system is put is much greater than that of the user. Finally, a fourth, *'user-led model'* can be envisaged, a system which may have similar technical characteristics to the producer-led model, but here the user can be seen to have a greater degree of control over system development, configuration and use, relative to the producer, and hence a much larger "footprint of influence".

Investigating the environmental potential of the producer-led model: the advanced home metering system

One of the aims of the project is to identify which model pathways are emerging most strongly in the UK and to highlight the tensions between the social, economic and environmental potentials of these different types of technical systems. In this paper we will focus on unravelling the environmental potential of some *advanced home metering systems* which are representative of the *producer-led model*. The potentials of such advanced metering systems are currently uncertain as they are relatively untried systems in the context of the UK domestic market. However, given that utility companies can use these systems to move "beyond the meter" to herald a new era of the 'smart' home, a radical restructuring of utility/user relations is likely, with significant implications, which need to be understood.

Marketing material from meter manufacturers is an ideal starting point for understanding the way in which advanced home systems are being promoted and what their implementation might mean for achieving more efficient resource usage patterns. The key messages which have emerged from some of these publicity brochures have been used to provide the basis for interpreting this *'producer-led'* metering approach. This has resulted in a deeper understanding of the wide range of technical, economic, social and environmental motivations which drive the actions of meter manufacturers and utility companies. From this interpretative process it has been possible to see the way in which producers and users are being ascribed particular roles around these types of metering systems, and consequently, how this is supporting or indeed constraining their environmental potential. Furthermore, some impediments inherent in advanced home systems have been identified, which will need to be modified if the environmental potentials of such systems are to be fully realised.

Possibilities for utility and user-led environmental action with the advanced home metering system

The overriding message being asserted by meter manufacturers promoting advanced home systems is that a new world of *unlimited potential* is opening up in which metering is pushed far beyond conventional electricity monitoring. The innovative new worlds of commercial opportunity which advanced home systems provide demand long-term perspectives and the emphasis in the advertising literature is on the potential for value-added benefits far into the future. Once the communications network opens up access to the home, there are vast possibilities for utility companies and other service providers to accrue benefits, including the potential for offering customers more comprehensive energy management options and moving beyond this to offer non-utility services such as home shopping and banking. Essentially, advanced home systems are represented by manufacturers as a *'whole new information medium'*, which will radically transform access to services in the home. Underpinning this message of unlimited potential are two ancillary messages, the first and most strongly asserted in publicity literature is one of *network control*, emphasising the potential for the utility to improve economic efficiency by adopting this type of system, secondly a more marginal message of *user choice* emerges. It is around these promotional messages that the story of the advanced home system can now be developed.

Implications of 'smarter' metering for utility network control

The message of network control for utility companies is that smart meters can open up a range of opportunities for both passive and active control of customers energy loads. These systems enable the pre-programming of tariffs, the enhanced display of a variety of consumption information to customers, and the application of load switching techniques, supported by the introduction of devices to control individual appliances in the home. In addition, the utility can use the system to closely monitor the lifestyle patterns of customers, effectively *'enabling supervision of all the users consumption'*, and opening up opportunities to target them for specific action, for example the selective marketing of particular services. Another issue that emerges from the message of network control is one of economic reassurance for the utility company. In the commercial electricity industry, limitless potential is meaningless if it is too expensive to implement these systems on a wide-scale. With this in mind, longer-term benefits are emphasised, as it is recognised that short-term investment in such systems is likely to be expensive. Therefore, a story is told by manufacturers of the numerous opportunities for the utility company to gain total control over the metering system and consequently over customers in the home, this message implying vast scope for utility-led environmental action.

However, in contrast to the messages being relayed by meter manufacturers, utility companies have shown only a guarded enthusiasm towards such systems. Interviewees in utility companies were sceptical over both the potential for longer-term profits and their viable utilisation as energy management solutions. The technological smartness of the system may have the potential to encourage energy efficiency, but, this potential is likely to remain under-utilised whilst companies are unconvinced of the commercial value of such 'smarter' metering solutions. However, despite the lack of commitment to the 'smarter' home future advocated by manufacturers, utility companies interviewed did envisage a time when these advanced metering systems would be necessary, as one utility representative noted: *'with the approach of the free market...we need to know at what time customers use electricity and the amounts they use'*. Therefore, the future potential of these systems keeps them as a firm contender for more widespread implementation in the UK domestic metering market. With this in mind, it is important to consider the issues which have been raised by a number of writers as to the more negative aspects of such systems (Crawford, 1995; Graham, 1996). Whilst the benefits of these systems might be seen as maximising long-term profits and saving energy they can also be configured as particularly potent tools for social control. For example, the surveillance capabilities of such systems might enable intrusive knowledge of customers lifestyle patterns, information gained can also be used as a particularly powerful marketing tool. In addition, given the high installation costs only the most lucrative of customers are likely to be able to afford these systems. This could create patterns of differential access to energy and other value-added services.

Implications of 'smarter' metering for user choice

Moving on from issues concerning utility-led manipulation of advanced home systems, it is also apparent that manufacturers are keen to convey a message of user choice. Customers are given a sense, albeit tentatively asserted, of a future home system which is responsive to their needs. Here, the incorporation of enhanced display units would improve access to consumption information and customer controllers could be provided for programming home energy management systems. However, whilst the opportunities for user action in the producer-led system appear to be extensive, on closer investigation the scope for using these facilities is not as clear-cut. For instance more sceptical interviewees reported that many user-choice features may only be *'add-on options'* for more sophisticated units. In addition the assertion that customers could programme their own energy management systems may be misleading, as the types of control possible are guided by the producer, as reported by one manufacturer: *'Customers...with a little help from the supplier, can optimise electricity consumption to minimise costs'.* Therefore, clear questions are raised as to how far users will be able to exercise choice over services and control their own energy management systems without the intervention of the producer. Another issue that needs to be considered is whether such extended choice is actually necessary to optimise environmental potentials.

Conclusions

A number of key questions and issues have been raised from the producer-led analysis undertaken. Essentially, the utility company controls the configuration of the metering system and as such sets the parameters for producer/ user action. Therefore, the environmental potential of such systems has to be meshed with the logic of commercial efficiency which guides utility company action in the privatised electricity industry. If we accept that a producer-led scenario can deliver environmental benefits a number of key questions are raised. Firstly, what financial incentives would be needed for customers to accept 'top-down' control of their consumption. Secondly, who would pay for the system components needed to facilitate environmental techniques. Finally, how widespread can such metering systems become in the domestic market. So far, there have been a number of positive signs that producer-led environmental management is possible. For example in the commercial sector, advanced metering technologies supported by energy management packages and advice from utility companies are encouraging energy efficiency, although the potential for translating these to the domestic sector is uncertain. In addition, a number of manufacturers believed there was consumer support for technologies which enable producer-led control. For example some 'smarter' users are prepared to make short-term expenditures such as buying modems to allow appliance load switching by the producer recognising that the financial benefits will justify this over the long-term. If utility companies can encourage and support such user collaboration, the environmental potential for producer-led control systems can be extended.

However, the *producer-led* metering scenario mapped out above can also restrict the contribution users can make to optimising their resource use. Our preliminary investigations of systems based on the *gatekeeper model* also show that the opportunities for energy management can be restricted by the distancing of the utility from the user. For instance, the potential for utility companies to offer dynamic pricing packages and real-time load switching is removed. Similarly, the user is unable to negotiate specific energy services. By contrast, a more *user-led* metering system may present new opportunities for the customer to understand their individual energy consumption and thereby configure their own energy management programmes. Of course, in this model we need to consider how far users can be relied upon to act in a way that benefits not only themselves but the wider environment. Clearly, maximising the environmental potential of 'smarter' metering systems will require not only 'smart' machines, but also 'smart' operators.

The aim of the investigation so far has not been to prescribe specific actions that have to be taken by utility actors, or indeed to suggest that one type of system is more desirable than others. Rather we hope to encourage a precautionary approach, advising and educating regulators, utility companies and government policy-makers as to the environmental implications of ascribing particular roles for producers and users in different metering systems. The answers to many of the questions raised in our investigations of different types of metering models will be addressed in a number of on-going case studies. Here, current trials of metering systems designed to test their contribution to energy management strategies have been selected. These further investigations will enable us to formulate more detailed technical and environmental policy guidance. Given that over the next decade we are likely to see the implementation and consolidation of many of these new metering systems in the UK this investigation into the potential options for extending the environmental benefits 'smarter' meters can offer is both essential and timely.

References

Allera, R.V. and Sturges, R.A. (1996) End-use monitoring with the 'POEM' system. In *Proceedings of the Eighth International Conference on Metering and Tariffs for Energy Supply*. Institution of Electrical Engineers

Crawford, R. (1995) Techno prisoners. In Gerbner, G., Mowlana, H. and Schiller, H.I. (1995) *Invisible Crises.* Westview Press

Dauncey, G. (1990) The role of metering technologies in combating the greenhouse effect. In *Proceedings of the Sixth International Conference on Metering Apparatus and Tariffs for Electricity Supply.* Institution of Electrical Engineers.

Dorey, H. (1991) Advanced Metering and Communications Technologies for Load Control. In *Proceedings of Conference on Advanced Technologies for Electric Demand-side Management*

Graham, S. (1996) Surveillant Simulation and the City: Telematics and the New Urban Control Revolution. Draft paper for presentation at the National Center for Geographic Information and Analysis annual conference. September 1996.

Guy, S. and Marvin, S. (1995) Pathways to 'Smarter' Utility Meters: The socio-technical shaping of new metering technologies. *Departmental Working Paper No. 51*

Redmond, S.J. (1994) The rationale for demand-side management. In *Power Engineering Journal.* October 1994

Whiteman, M.E. (1996) Applications of Distribution Automation and Demand side Management in AMR Systems. In *Proceedings of the Eighth International Conference on Metering and Tariffs for Energy Supply.* Institution of Electrical Engineers

Movement and deposition of aerosol particles in buildings

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Summary

This paper examines the relationship between air flow and the deposition rate of aerosol particles in a ventilation systems and single-zone chamber. Measurements were performed to study the flow of aerosol particles in a small scale HVAC system fitted with different types of fittings. A computational fluid dynamics (CFD) package FLUENT, simulated the particle flow, and results were compared with the experimental. Results show that in HVAC systems, to minimise dust problems, use high speed less intricate ducting. In a single-zone chamber, a course filter should be used to remove large particulate, whilst a carefully chosen ventilation strategy should be implemented.

Introduction

Heating, ventilation and air-conditioning (HVAC) ducts are used widely in modern buildings, but can be contaminated by aerosol particles penetrating the filters. The particles deposited on the duct walls facilitate growth of bacteria, micro-organisms and viruses that are then transported to the occupied spaces. Studies have shown that deterioration of indoor air quality(1) is contributed too by the deposition of aerosol particles in ducts. There is a need for a fundamental study of particle behaviour inside ventilation ducts, so that effective measures for minimising particle deposition can be formulated. Development of techniques that could be used to remove aerosol particles, requires knowledge of airflow rates, concentrations, particle sources and sizes. The micro-electronic and pharmaceutical industries require clean working environments, with low particle concentrations and control of particle movement in buildings, such as hospitals, is necessary to prevent flow of contaminated air to other rooms(2). A study of particle behaviour within a single chamber has also been completed. This shows how particle movement is also governed by the different ventilation strategies used.

The work covered in this paper carries on from work completed by Adam et. al.(3), where aerosol particles and tracer-gas were measured experimentally and an initial CFD model was used for a simple comparison. The work presented here shows a detailed CFD simulation. This provides graphical information that relates deposition ratio with air flow rate for eight types of fitting. It also supplies air exchange efficiencies for a single-zone chamber.

Experimental work

The experimental work was carried out using the duct system shown in Figure 1, and a single-zone chamber shown in Figure 2. The duct was constructed from galvanised mild steel and with a square cross-sectional area (0.3m x 0.3m). The downstream end was connected to an axial fan by means of a diffuser. Static, velocity pressure and particle tappings were positioned along the duct.

The experimental procedure involved injecting oil smoke ($0.5\mu m < d < 2\mu m$) into the duct inlet with the fan off. Once a uniform concentration was achieved, the dust monitors were switched on simultaneously and the fan was switched on to a predetermined speed. The oil smoke concentrations were measured continuously using infra-red particle monitors. A series of four different airflow rates were used for the following fittings:

(i) Straight Duct.

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(ii) Reducer.
(iii) Single 90° bend.
(iv) Double 90° bend.
(v) Dampers:- The plate was angled - at 0°, 30°, 45°, and 60° to the flow.

Particle and tracer-gas concentrations were monitored using the concentration-decay technique, this technique is time dependent and so transient. To be able to compare this transient flow with the steady-state CFD simulation, the experimental results were manipulated into a meaningful form. The raw experimental data gives a list of concentration values for each geometry and flow rate for the two measuring stations. These concentration values were taken for every minute that the experiment was running, usually about 20 minutes. For each of these values, the deposition ratio, Dr, is calculated:

$$Dr = \frac{C_A - C_B}{C_A}$$

where C_A and C_B are the concentrations of aerosol particles for each time interval throughout the experiments. For each geometry and flow rate, the deposition ratio is averaged over the time range of the experiment:

$$Dr_a = \frac{1}{n} \sum_{n=1}^{n} \frac{C_A - C_B}{C_A}$$

where n is the number of time intervals. When this is complete, it gives a steady-state representation of particle concentration and can be compared with the dispersed phase concentration obtained from the CFD analysis. The steady-state concentration technique was not used in the experiment due to the large amounts of expensive tracer-gas needed, to obtain sound and steady results.

The experiment for the single-zone chamber completed in a similar manner. Aerosol particles were injected into the chamber with all dampers closed and fans off. Once a uniform concentration had been achieved, the diffusers were opened and the fans switched on. The measurement of concentration of the particles immediately commenced at the centre of the chamber and exhaust duct. The relative ventilation efficiency and average air exchange efficiently were calculated using the following formulae:

$$\eta_r = \frac{C_e}{C_i} \qquad \eta_a = \frac{\tau_e}{\tau_i}$$

where τ_e is age of air at the exhaust, and τ_i is the age of air at point I. The five ventilation strategies considered can be seen in Figure 3.

CFD analysis

The importance of CFD has been outlined by Shaw[4], who reported that two major disasters might have been avoided if CFD studies had been held at the two sites. This prompted increased investment of time and money to produce more powerful, yet easier to use CFD packages.

In this investigation the CFD package FLUENT V4.2, was used for all numerical simulations. FLUENT V4.2 comes in two sections. The first, preBFC, is a CAD type package. The second section is FLUENT itself. In this section all the physical constants and boundary conditions are entered, and the correct models are activated.

Continuous flow modelling

All the flows under investigation are 3D, steady-state, incompressible turbulent flows. Although the fluid used is air, it can be considered incompressible due to the relatively low flow rates used. Temperature and gravitational force will also be considered.

In the FLUENT User guide[5], the calculation procedure, uses conventional equations, those adapted from the conservation and Navier-Stokes equations. To make them relevant for turbulent flow, the equation set is closed via the Reynolds time averaging procedure and the k-ε closure model. The k-ε closure model was used to simulate these complex internal flows due to the amount of research completed using this method. In the k-ε model the velocity and length scales are obtained from the parameters' k, the turbulent kinetic energy and ε, the dissipation of k. The values of k and ε are obtained by solution of the conservation equations.

For each fitting four different inlet velocities were modelled, the inlet velocity was entered as a uniform profile, a length of 1.7m was allowed before the first measuring station to ensure a fully developed flow. The turbulence inlet profile was calculated by entering values for the turbulence intensity and characteristic length.

Dispersed phase modelling

Oil smoke particles were injected into the continuous flow. These particles have a density, ρ = 865 Kg/m^3, and a heat capacity, Cp = 2000 J/Kg.K. It is assumed that the particles are spherical and that they deposit on the duct walls after colliding with the walls. One hundred particles of diameter 2μm were uniformly distributed in the cross-section slightly upstream of the first measuring station. A stochastic tracking procedure was run five times which allowed the fate of five hundred particles to be tracked.

Prediction of the trajectory of a dispersed phase particle, shown in the FLUENT User Guide[4], is done by integrating the force balance on the particle which is written in Langrangrian reference frame:

$$\frac{du_{p.i}}{dt} = F_D\left(u_{\infty.i} - u_{p.i}\right) + \frac{g_i\left(\rho_p - \rho_\infty\right)}{\rho_p} + F_i$$

where $F_D\left(u_{\infty.i} - u_{p.i}\right)$ is the drag force per unit particle mass

and $$F_D = \frac{18u}{\rho_p D_p^2}\frac{C_D \mathrm{Re}}{24}$$

where μ is the molecular viscosity, ρ_p is density of particle and D_p is the diameter. The drag coefficient C_D is a function of the relative Reynolds number. The dispersed phase includes heat transfer to and from the continuous phase.

Due to the inadequate boundary conditions allowed by the CFD package, particles stay deposited on the duct walls after contact is made, no reflection or re suspension is permitted. This will give rise to a greater deposition ratio than would be expected, but should be independent of the air flow rate, but dependent of the type of fitting.

Results and discussion

Comparisons for the deposition ratio were made for the eight types of geometry. For each of these geometries, experimental and CFD analysis was carried out for four flow rates. Relationships for particle deposition ratio, as a function of flow rate, for both experimental and CFD results are shown for the selected geometries, Figure 4 for the reducer, Figure 5 for the double bend.

For all of the comparisons, the experimental and CFD results follow the same trend but a larger deposition ratio is obtained with the practical results. This can be explained firstly due to the experimental measuring equipment only allowing accuracy to within five percent, and secondly the CFD assumption that particles are trapped onto the boundary surface when contact between them is made, not allowing any re suspension of particles.

For all the fittings the deposition descends as flow rate increases, and the deposition ratio is approximately 5% higher for aerosol particles than it is for tracer-gas. By inspection, the particles follow the general shape of the flow, but do however become caught in the turbulent boundary layer, this is when deposition occurs.

Typical relationships for the relative ventilation efficiency against time and the concentration with time can be found in Figure 6 and Figure 7 respectfully, for the single-zone chamber. A variety of particle trajectories calculated by CFD are shown in Figure 8.

Conclusion

For the HVAC fittings the results indicate that:

1) The deposition ratio is effected by the type of fitting used. The highest deposition rate occurred in the damper and the least in the reducer. It is advisable therefore to have the simplest arrangement of ductwork avoiding, if possible, fittings such as dampers and 180° bends.

2) Increasing flow rate produced a decrease in the deposition ratio. Therefore it is advisable to install higher speed ducting in order to minimise dust problems in HVAC systems.

For the single-zone chamber the results indicate:

1) The relative ventilation efficiency and average exchange efficiency were found to be large and dependent on the ventilation strategy. It is therefore highly advisable to research the best ventilation strategy before building the final system.

2) The deposition rate increased with increasing particle size. This indicates that large particles cause the most serious problems. Introducing a coarse filter will reduce this problem.

These results provide evidence that CFD can be a useful tool for predicting deposition of particles on duct walls, especially if the boundary conditions were more flexible. It also provided results for particle movement within a single-zone chamber.

Acknowledgements

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References

1 Turiel I Indoor air quality and human health Stanford University Press Stanford California (1985)

2 Farrance K. and Wilkinson J., "Dusting Down Suspended Particles", Building Services, 12, 45-46, (1990).

3 Adam N., Riffat S. B. and Shao L., "Deposition of aerosol particles in ventilation ducts", Proceedings Aerosol Society 9th Annual Conference, 116-121, Norwich, U. K., April 4-6, (1995).

4 Shaw C. T., "Using Computational Fluid Dynamics", Prentice Hall International Ltd, Hemel Hempstead, Hertfordshire, England, 1-3, (1992).

5 FLUENT, "User Guide", Fluent Incorporated, Lebanon, (1993).

Figures

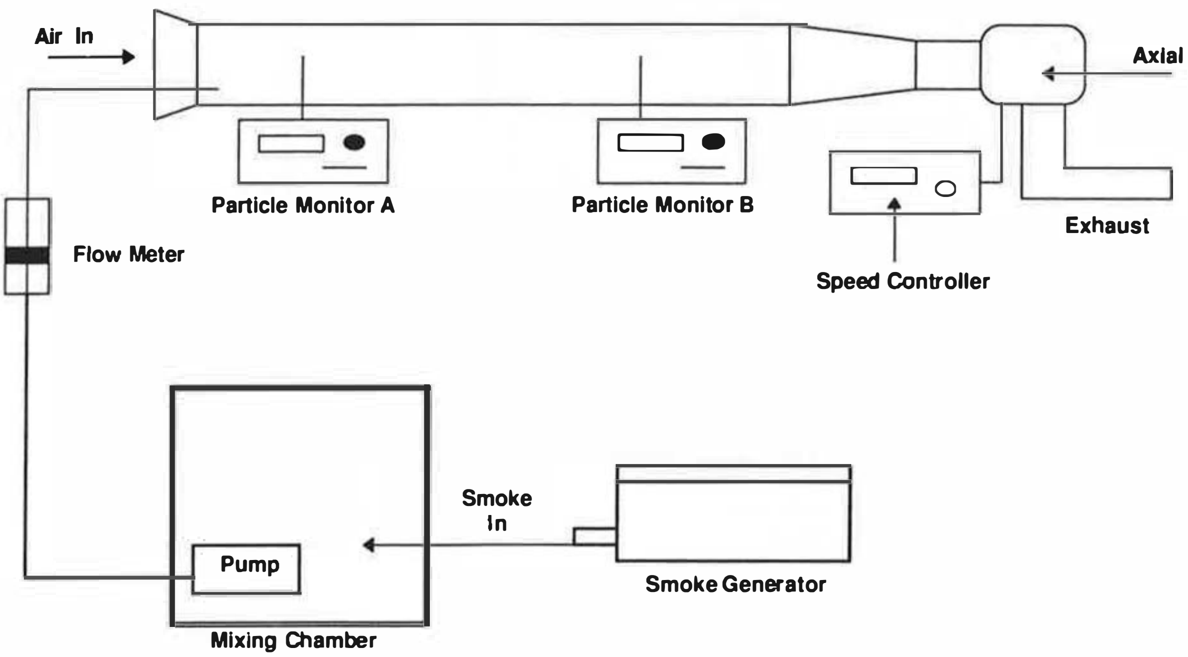

Figure 1: Schematic of test rig and instrumentation

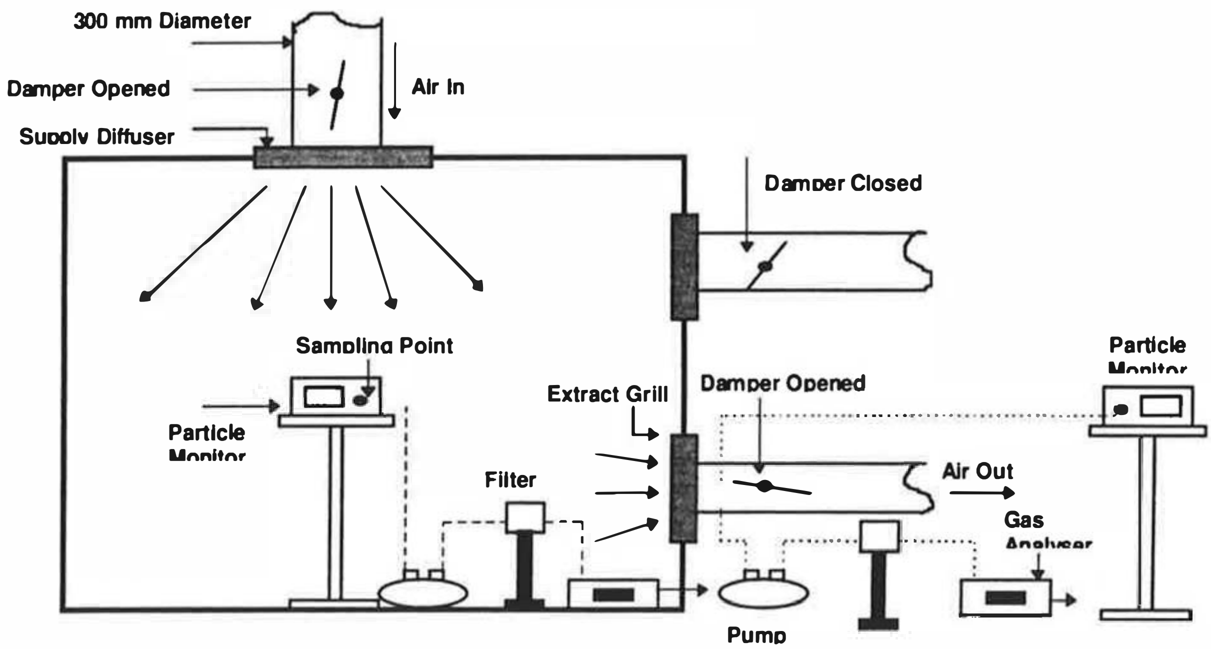

Figure 2: Schematic of the chamber and instrumentation

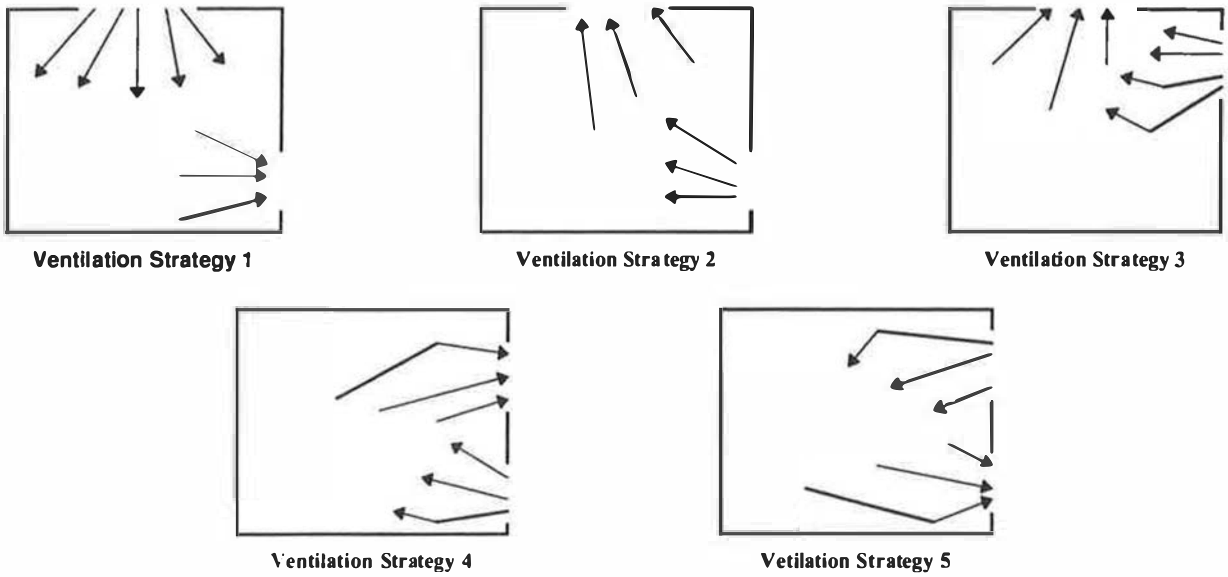

Figure 3: Different ventilation strategies

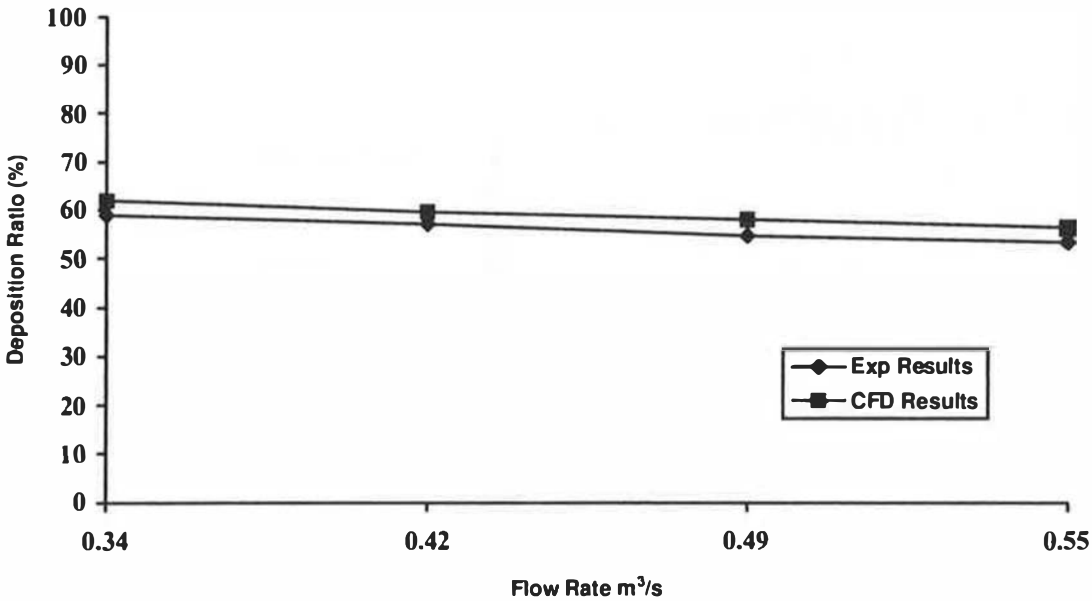

Figure 4: Comparison of experimental results against CFD results for oil smoke deposition in a reducer

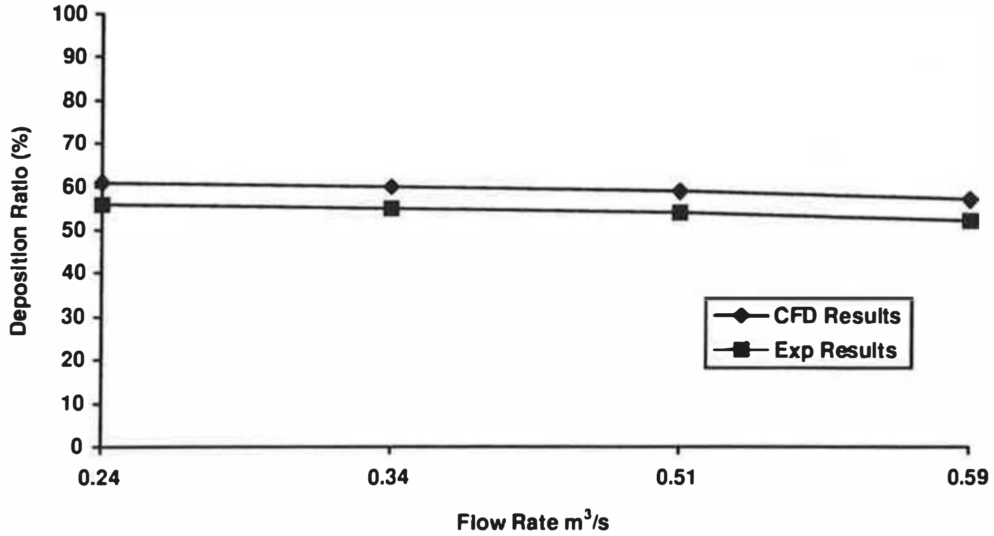

Figure 5: Comparison of experimental results against CFD results for smoke deposition in a double bend

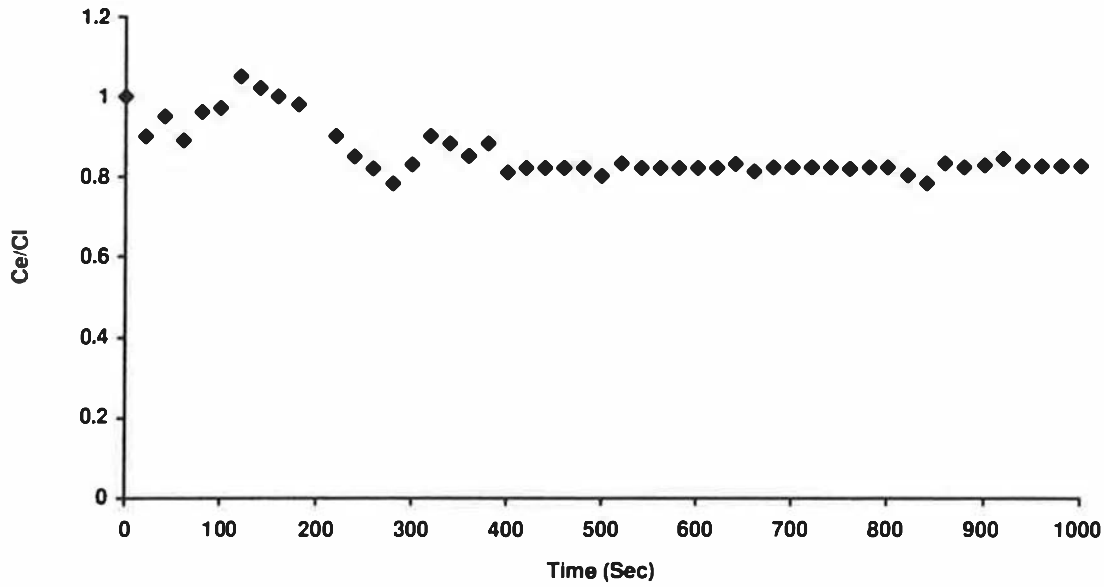

Figure 6: Variation of relative ventilation efficiency with time for air change rate at 7.1 h^{-1}, tracer gas

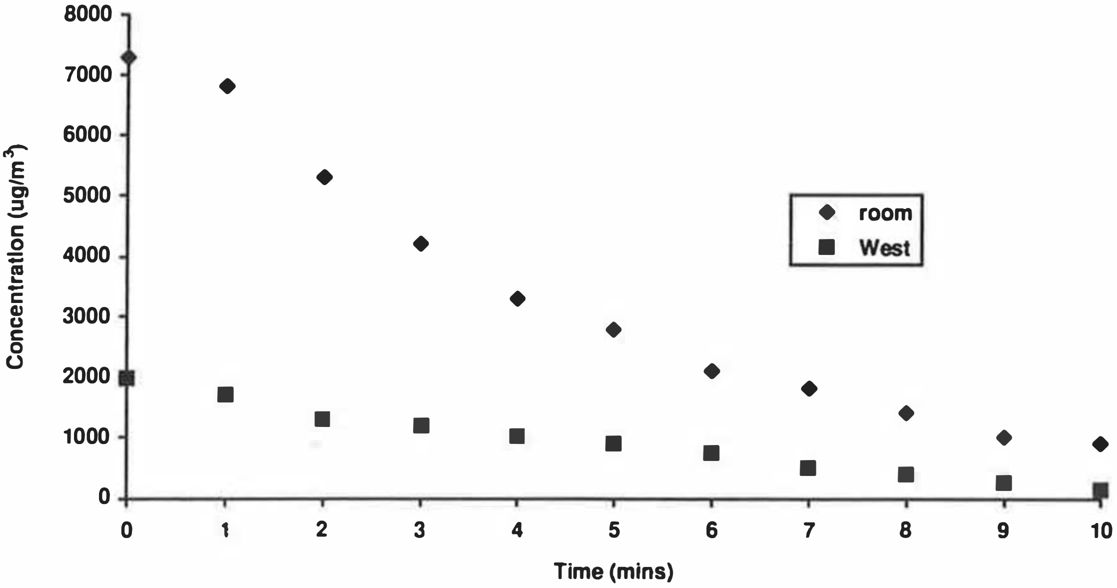

Figure 7: Variation of concentration with time for air change rate at 17 h^{-1}, particle

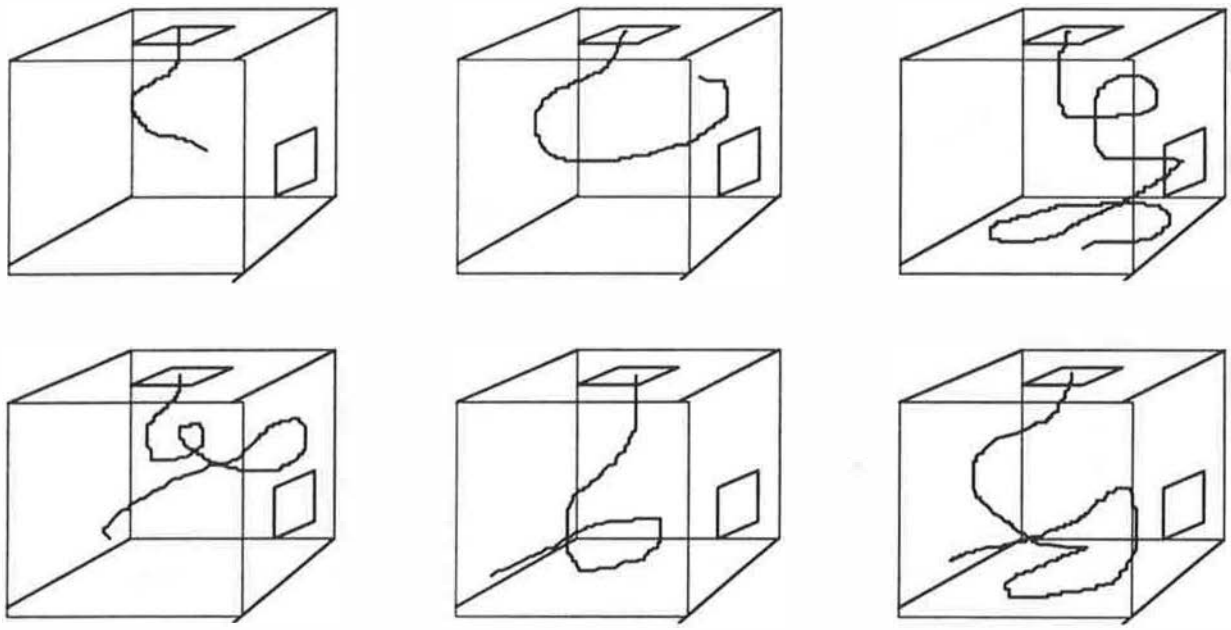

Figure 8: Trajectories of particles with various original positions and diameters

ENERGY EFFICIENCY BEST PRACTICE PROGRAMME

HEAT PUMPS IN THE UK:

CURRENT STATUS AND ACTIVITIES

General Information Report 67

Prepared for the Energy Efficiency Best Practice Programme by ETSU, Harwell, Didcot, Oxfordshire OX11 0RA.

General Information Report No 67 **February 2000**

The work described in this report was carried out under the Govenment's Energy Efficiency Best Practice Programme which is aimed at advancing and disseminating impartial information on ways to improve the efficiency with which energy is used in the UK.

Further copies of this report can be obtained from the Energy Efficiency Enquiries Bureau, ETSU, Harwell, Didcot, Oxfordshire OX11 0RA. Fax No: 01235 433066.
Helpline Tel No: 0800 585794. Helpline E-mail: etbppenvhelp@aeat.co.uk

MANAGEMENT SUMMARY

This report covers heat pumps in domestic buildings, commercial buildings, and industry. Because of the importance of environmental considerations, appropriate emphasis is given to the perceived impact of heat pumps on CO_2 emissions.

The commercial buildings sector is by far the most prolific in terms of the number of units used, although their cooling capability dominates in terms of energy use. The domestic sector is currently relatively inactive, although interest in R&D is high, with several projects under way. The potential for heat pumps in industrial processes is high but, with one or two exceptions, market uptake has been poor, inhibited by low energy costs.

The last few years have seen a much greater participation by both UK bodies and other organisations in international activities in the heat pump field. In addition, the number of national groupings has also increased. The further linking of UK and overseas activities could result in the benefits of the technology being more effectively transferred to the user sectors.

CONTENTS

1. INTRODUCTION

The UK has a long history of active involvement in heat pump technology, stretching back into the last Century with the first demonstration of a domestic unit. In the early 1970s, the first oil crisis led to a rapid growth of development in heat pump technology, both here and overseas. The UK was not slow in recognising that heat pumps could benefit the growing demand for energy-efficient systems in all sectors.

In spite of reservations concerning the market penetration of heat pumps achieved in the UK to date, companies have shown an increasingly positive attitude towards heat pump technology and use. This is reflected in projects such as *Rotex*, which is at the forefront of absorption cycle technology. Internationally, the UK takes an active part in programmes such as the *International Energy Agency's* (IEA) *Heat Pumping Technologies Programme* and various *European Union* programmes. At home, developments are facilitated by the extensive networking activities established by organisations such as ETSU and BRECSU for the *Energy Efficiency Best Practice Programme* (EEBPP), and the *Heat Pump Association* (HPA).

This review of the current status of heat pumps in the UK, and associated activities, reveals that the UK is now in a strong position to grasp any opportunities, both here and in overseas markets. This arises out of the perceived need for heat pumps as a component of a strategy for energy efficiency and environmental protection. Similarly, where improved living and working conditions are continually expected, the UK manufacturing base for heat pumps used for both heating and cooling is in an increasingly strong position to meet any growth in demand. However, it should be noted that this is not always compatible with the need for reduced CO_2 emissions.

2. THE ATTITUDE OF THE DECISION MAKERS IN THE UK

Official funding organisations in the UK have historically taken the lead in putting a strong emphasis on the cost-effectiveness of research and subsequent downstream activities, such as demonstration. This realism, which is linked to the need for a visible return on the investment from developments, including heat pumps, can create difficulties for innovation. However, it does place sensible, practical constraints on the use of available support.

Perhaps the most important factor raised in the discussion of heat pumps is the effect they could have on CO_2 emissions. In each of the market sectors discussed below, the 'green credentials' of heat pumps are discussed. For further details see General Information Report 68, *Heat Pumps in the UK: The Environmental Case* [1]. It will become obvious that Government policy relating to industry and, to a lesser extent, to commercial buildings, is becoming more favourably inclined towards heat pumping technologies.

Of course, Government, and the other bodies involved in decision-making in the area encompassing heat pumps, has to weigh the advantages and disadvantages of many competing systems. Heat pumps can be operated using any one of three principal thermodynamic cycles, each depending on different fuels and different working fluids. In each case, the environmental impact may be different, with possible positive or negative consequences.

As this report demonstrates, the UK is fortunate in having highly competent researchers, with the capability of reacting to switches in emphasis between technologies, in all three areas. The excellent work carried out in the UK on passive heating and cooling systems, renewable energy technologies and other forms of active heating and cooling have significantly helped decision-makers to select and support the appropriate technologies for each potential application.

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1 The publications detailed in this report are available through the Environment and Energy Helpline on freephone 0800 585794.

3. THE UK MARKET POSITION, MAJOR USES AND POTENTIAL NEW APPLICATIONS

This Section details the position of the market for heat pumps in the UK, including information on the major uses, potential new applications, and R&D activities for the three principal sectors (domestic, commercial and industrial). Section 4 contains a summary of the R&D work underway on general heat pump-related areas.

The most recent data on the market position of heat pumps in the UK (covering all sectors) was compiled for the UK National Position Paper for the *IEA International Heat Pump Status and Policy Review* report in 1998.

Domestic Heat Pumps

The UK market position

Since 1992, approximately 3,000 heat pumps have been installed in single-family homes in the UK, plus a negligible number in multi-family homes, (very approximate estimates from the *Building Services Research & Information Association* - BSRIA). Approximately 40% of the installations are believed to be air-water heat pumps for domestic swimming pools. The domestic market forms approximately 1% of the market for split air conditioning systems, most being installed in conservatories, with 25% of these being heat pumps. The domestic market for heat pumps for ventilation heat recovery is currently negligible, but there is some growth in the use of portable air conditioners in homes due to active promotion. One type of heat pump not included in statistics is the domestic dehumidifier. Although many thousands have been sold, there is no attempt to market domestic dehumidifiers as heating devices. However, in principle there is no reason why a heating capability could not be promoted, as with industrial dehumidifiers for batch industrial dryers.

One of the main factors affecting air-to-air and air-to-water electric drive vapour compression cycle heat pumps for the domestic market in the UK is the low Coefficient of Performance (COP). Averaged over the year, this is in the range 2.0 - 2.5. The actual COP can drop below this range when outside ambient temperatures are very low and supplementary heating would be required (normally electricity when an electric heat pump is installed). When COP levels approach 3, heat pumps can be regarded as cost-effective, assuming that the capital cost will not increase as COP increases, and that domestic electricity and gas tariffs remain similar. Other benefits, such as a healthier living environment, less dampness and structural degradation, may also be influential on market development.

The use of ground as a heat source for domestic heat pumps (GSHPs) is of obvious interest because of its small seasonal temperature fluctuations and relatively high temperatures, when compared to air in winter conditions. Several units have been installed in the North of Scotland in houses. When installed in 'new build' houses where mains gas is not available, with COPs of about 2.8, they provide a competitive option to direct electric heating. However, a monitoring activity by BRECSU on a GSHP linked to underfloor heating has reported that a COP of slightly less than 3 can be affected by the pump power. With relatively small domestic heat pumps (5 kW output), the need for supplementary heating and direct electric immersion heaters for hot water has an additional negative impact on energy use/CO_2 emissions.

There are no absorption heat pumps in the UK domestic sector, but the *Rotex* unit (see below) is to be evaluated in a dwelling in Didcot, Oxfordshire. This unit offers cooling as well as heating, using gas as the fuel.

Potential new applications for domestic heat pumps

The small size of the current domestic heat pump market suggests that it will favour an expansion of market penetration for existing heat pump types rather than providing a springboard for new application areas. Principally, these are likely to be electric drive vapour compression cycle units. The use of electricity is hindered by the current UK preference for gas-fired wet central heating systems, with strong marketing of the condensing boiler as the current technology for improving energy efficiency. Also, in the heating-only market, the high cost of equipment based on heat pump cycles inhibits penetration. The capital cost is not aided by the higher price of HFC refrigerants, now becoming necessary due to environmental legislation.

Conservatories are seen by some companies as a significant market for heat pumps, enabling summer cooling and an extension of conservatory use into spring and autumn, with units operated in the heating mode.

BRECSU sees a need to inform industry (i.e. suppliers and system installers) of the opportunity for a heat pump option in future houses, while emphasising the requirement for seasonal COPs of 2.7 - 2.8, where auxiliary heating is not being used.

There is an increasing trend towards using ventilation heat recovery heat pumps in the home and, while the market is currently very small, more companies are offering products. It is possible that, as more home owners invest in heat recovery ventilation units (not based on heat pumps) and houses become increasingly 'leak tight', the logical upgrading of such systems to incorporate heat pumps will grow in popularity. Of course, extract air can improve heat pump COP by using the heat recovery unit to preheat air upstream of the evaporator. Fortunately, the UK is proficient at designing and manufacturing appropriate heat recovery units for such duties.

BSRIA published data early in 1999 suggesting that domestic air conditioning would grow at a substantial rate in future years. While this is seen as a 'niche' market for executive homes in Southern England at present, the relatively inexpensive incorporation of reversibility to provide heating in small air conditioning units could provide a more rapid route to acceptability of heat pumps in the domestic sector. Again, the effect on UK CO_2 emissions due to increased electricity use by such systems must be considered. As an example, BRECSU have expressed concerns that, even where heat pumps for heating only might be installed (in executive-type homes), if they were to be used additionally at a later stage for cooling, the effect on CO_2 emissions would be negative.

This discussion has concentrated on electric drive systems. However, if absorption cycle heat pumps can be made at a competitive cost, and with a COP of about 1.5 (the approximate target for the heating COP of *Rotex*), gas costs to the user for whole house heating could be reduced by almost 50%. In addition, emissions from domestic heating sources would be proportionally lower.

Research and development on domestic heat pumps

In the area of domestic heat pumps, the largest R&D exercise in the UK is that led by *Interotex Ltd* in Cheltenham, with strong support from *BG plc*, *Lennox* and the *European Union.* Now, in a THERMIE demonstration project, double effect absorption units are being installed for evaluation in a number of test houses throughout Europe. These will have a heating and cooling capability.

There is interest in integrating renewable energy sources with heat pumps. At *Nottingham University*, a wind energy generator is being evaluated as a possible supplementary source for driving the compressor of a vapour compression cycle unit. A recent UK-led CRAFT (EU) project examined the use of compact heat exchangers as the basis of solar-assisted absorption air conditioning units. However, under present climatic conditions, markets for such equipment are more likely to be in Southern Europe.

BRECSU have also been considering the operating costs of systems and what target costs might be appropriate. For example, the ability to provide heating and cooling for no more than the cost of gas heating would be of considerable interest. However, the need to reduce CO_2 emissions must be at the forefront of any development.

Heat Pumps in Commercial Buildings

The UK market position

This is the most prolific area of heat pump application in the UK, the majority of the systems providing heating and/or cooling. Air conditioning is driving the market, with overall UK penetration in offices, hotels and retail outlets approaching 25% and 50% for central London. Annual heat pump sales to this sector in 1996 numbered 55,600 units. Significantly, the amount of heat provided by reversible heat pumps in commercial buildings remains relatively small - less than 0.2% of the heating needs - emphasising the dominance of the cooling duty. The Government is actively presenting the alternatives to air conditioning but, realistically, it is considered prudent to give guidance to this sector on system choices that will lead to energy savings.

In terms of electric drive vapour compression cycle machines, the larger buildings sector may be regarded as a mature user of heat pumps. However, it is noticeable that buildings such as hospitals have a much lower use of heat pump systems. The most 'high profile' use of heat pumping systems in hospitals and similar large building complexes involves using the exhaust heat from CHP systems to drive absorption cycle chillers.

Where the emphasis is particularly on cooling, absorption cycle machines are making growing inroads into the buildings market, but the proportion remains small. Their market share is anticipated to increase in the future, due to active marketing by *Transco*, with supporting effort by *BG Technology.*

Potential new applications for commercial heat pumps

The market growth in building air conditioning is of the order of 5% per annum, with installed capacity and energy consumption likely to at least double by 2010. Further information is contained in the Air Conditioning paper published under the Government's *Market Transformation Programme* (see web-site: www.mtprog.com).

example being the work at *Sheffield University* on membrane distillation processing. In this instance, a heat pump is proposed to facilitate heat input and removal.

R&D is also being carried out on systems that combine heat pumps with other energy input techniques. A notable example is the radio frequency assisted heat pump batch dryer at *Cambridge University*, where radio frequency heating helped moisture migration to the outside of particles being dried.

4. A SUMMARY OF HEAT PUMP R&D IN THE UK

The greatest proportion of R&D activity on heat pumps in the UK focuses on improving sorption cycles. This includes absorption and adsorption, where the latter uses a solid and a gas as adsorbent and refrigerant respectively, rather than the vapours and liquids used in absorption machines. Much of the R&D is equally applicable to the commercial buildings sector, as the cycle remains similar regardless of unit heating/cooling capacity. *Warwick University* is active in adsorption heat pump R&D, and *Nottingham University* and *Bristol University* also have interests in this area. In the past, studies have been carried out into Stirling cycle heat pump and refrigeration machines (*Cambridge University*), but most activity in this area is now directed at Stirling machines for combined heat and power production in the home. *BG Technology* is researching a Stirling engine-based domestic CHP unit. This may open up opportunities for either heat-actuated or electric drive heat pumping machines. *EA Technology* is researching a Stirling cycle domestic refrigerator.

The need to replace CFCs and HCFCs has necessitated research on alternative working fluids. Commonly, these include HFCs, such as R134a, or HFC mixtures, where evaporator and condenser performances are affected by the different boiling and condensing temperatures of each component. *Leeds University* is active in this area, in conjunction with *Airedale Air Conditioning Ltd.* The *University of Ulster* has extended such analyses to compressor and lubricant behaviour, with hydrocarbon working fluids. *Brunel University* is involved in modelling systems using refrigerant mixtures.

Full details of university-based R&D can be found in the General Information Report 70, *Heat pumps and heat pump related R&D in UK universities.*

The extensive work in areas such as heat transfer - critical to efficient heat pumps – is not to be neglected. Even if initiated within a separate programme, the successful transfer of improved heat exchangers, such as to the heat pump industry, can bring substantial benefits. These may be reflected in equipment first cost and coefficient of performance.

5. CONCLUSIONS

The commercial sector is the most prolific user of heat pumps, although the use of the air conditioning plant for heating is relatively modest. The domestic sector remains dominated by gas-fired conventional wet central heating systems, with the potential for heat pump technology seen as largely in 'new build' houses. There are niche markets in the process sector but, as uptake has been modest, new initiatives within the context of broader sector energy efficiency activities are planned.

In the domestic and commercial buildings sector, there is a strong Government emphasis on minimising CO_2 emissions, and this affects heating and cooling system development and marketing. There are opportunities to improve equipment COP or to use cycles other than electric-drive vapour compression units in order to produce less negative environmental effects.

In industry, it is possible to identify growth areas and new applications, but increased activity by the suppliers of equipment is needed to fulfil any growth in demand for process heat pumps.

As in many other fields, the R&D community in the UK is very active and participates in many international programmes. Much of today's R&D could lead to increased export opportunities for UK-manufactured plant.

APPENDIX 1

INFORMATION AND NETWORKING ORGANISATIONS INVOLVED IN HEAT PUMPS IN THE UK

UK Organisations

BG Technology: the Gas Research Centre is active in the development and support of absorption technology and has links with gas utilities worldwide. Contact BG Technology, Ashby Road, Loughborough, Leicestershire LE11 3ER.

British National Committee on Electroheat (BNCE): promotes electroheat technology in the process industries, including heat pumps; active in the IHPTF. Contact via The Electricity Association, 30 Millbank, London SW1P 4RD. Telephone 020 7963 5700.

EA Technology: active in the IEA Heat Pump Implementing Agreement. Developed MVR systems. Contact Russell Benstead, EA Technology, Capenhurst, Chester CH1 6ES.

Energy Efficiency Best Practice Programme (EEBPP): provides impartial, authoritative information on energy efficiency techniques and technologies. Managed on behalf of the Government by: BRECSU (Buildings Research Establishment) for buildings applications, which covers heat pumps in domestic and commercial buildings, and can fund R&D; and ETSU for industry applications, notably for refrigeration and heat pumps. Contact via the free Environment and Energy Helpline on 0800 585794.

Engineering & Physical Sciences Research Council (EPSRC): funds university research, including heat pump-related projects. Contact EPSRC, Polaris House, North Star Avenue, Swindon SN2 1ET.

The Heat Pump Association (HPA): represents UK heat pump suppliers, and provides network and other forms of support; active in international committees; principally concerned with heat pumps in buildings. Contact Tony Bendall, c/o FETA, Henley Road, Medmenham, Marlow, Buckinghamshire SL7 2ER. Web-site: www.feta.co.uk

UK Heat Pump Network is supported by the *Department of the Environment, Transport and the Regions* (DETR) *via* ETSU, DTI and the HPA. This is a networking activity to promote the use of heat pumps to economic and environmental best practice and is managed by Dr Sandra Gomez of the **Building Services Research & Information Association (BSRIA)**, V Wing, TRL, Old Wokingham Road, Crowthorne, Berkshire RG45 6XA. Telephone 01344 750515. Fax 01344 487575. E-mail sandra.gomez@bsria.co.uk.

Overseas and International Organisations

International Energy Agency (IEA): an intergovernmental organisation under which the IEA Heat Pumping Technologies Programme operates. Contact IEA, Public Information Office, 9 rue de la Federation, 75739 Paris Cedex 15, France. Telephone (33-1) 40 57 65 54. Fax (33-1) 40 57 65 59. Web-site: www.iea.org

IEA Heat Pump Centre (HPC): the centre of expertise and heat pump information for the IEA Heat Pumping Technologies Programme; hosted by Novem, the Dutch Energy and Environment Agency in the Netherlands. It disseminates analysed data on heat pumping technologies and markets and operates on an international basis, and the UK is a member country. Contact Novem, PO Box 17, 6130 AA Sittard, The Netherlands. Web site: www.heatpumpcentre.org

The European Commission (EC): *via* DG12 and DG17 in particular, supports R&D in heat pumps in buildings and, to a lesser extent, industry; also supports networking activities. Can be contacted via CORDIS web-site: www.cordis.lu.

FIZ: a technical institute in Karlsruhe, Germany; hosts the German Heat Pump Centre; manages the EC network activity on heat pumps; web-site incorporates data bases on manufacturers, EU R&D projects, etc. Web-site: www.FIZ-Karlsruhe.de.htm/