MODELLING THE THERMAL BEHAVIOUR OF INDUSTRIAL BUILDINGS

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1. Introduction

In order to model the thermal behaviour of industrial buildings, certain special features must be taken into account. Such buildings usually consist of one or two large zones, in which temperature stratification and air movement patterns cause considerable spatial variations. The usual assumption that each zone is at a uniform temperature does not hold. Convection coefficients at internal surfaces are known to be important (1), and the modelling of these coefficients over large surfaces, especially the underside of pitched roofs, requires careful consideration. Also, the majority of industrial buildings have a large floor slab in contact with the ground. Because of its potential for thermal storage, this floor slab must be accurately modelled. The usage of these buildings also requires careful consideration. They are often subjected to a variety of high level heat gains and high ventilation rates during occupancy, with complete shut down when not in use. The objective was to develop a high quality thermal model suitable for industrial buildings, and to use it to study those features which are of greater significance for energy consumption.

2. The modelling process

A review of available techniques suggested that the finite difference method has a slight advantage over others, mainly due to its inherent flexibility, and a decision was taken to use this method. However, previous experience with a model of this type (2) showed that anomalous results are sometimes generated. Therefore seven types of finite difference approximation to the heat conduction equation have been investigated. The schemes examined were (i) explicit, (ii) implicit, (iii) Crank-Nicolson, (iv) Douglas, (v) modified Crank-Nicolson using three time levels for the central node, (vi) modified Douglas using three time levels for the central node, and (vii) a scheme using three time levels for the central node and both adjacent nodes.

These schemes were applied to single and two-layer walls constructed of typical building materials, and the results compared with analytical solutions. It was found (3) that the relative performance of the schemes changed according to the specific problem, and that the more complex schemes, although theoretically superior on the basis of truncation error analysis, were not always the most accurate, especially where the wall was two-layer. Most of the schemes exhibited poor behaviour (instability, oscillation, or large errors) in at least one of the tests. For the wide variety of constructions present in most buildings the implicit scheme appeared to be preferable. Although not highly accurate, it was always stable and oscillation free. It does not produce the very large errors at thin surface layers which the other schemes investigated here appear to do, and which could have a particularly bad effect on a building thermal model.

The method of distributing nodes in multi-layer walls was investigated first by truncation error analysis, and then by trial calculations on multilayer walls. It was concluded (4) that errors arising from the space discretization process could be kept close to a minimum by first placing nodes on the internal boundaries between materials, and then distributing any additional nodes in such a way as to maintain approximately the same mesh ratio in all materials.

Industrial buildings differ from other building types because the surfaces facing a given space are often much larger, and the ceiling is often sloping because it is the underside of a pitched roof. Therefore equations for convection coefficients were formulated by combining the results of several workers in this field, especially Alamdari and Hammond (5), and Fujii and Imura (6). Even so it was not possible to resolve completely the problem of heat transfer at a horizontal surface adjacent to a stably stratified air layer (7). This is of particular concern with respect to the large floor areas that are common in industrial buildings. Radiation exchange between internal surfaces was treated by means of the usual formulae, though it was found that it was possible to simplify the calculation of configuration factors without undue loss of accuracy.

The method adopted for the modelling of the floor slab is an extension of work by Delsante et. al. (8). The heat flow to and from the surface of the floor is considered as the sum of three components:

(i) a steady-state flow along curving paths, resulting from the difference between the annual averages of internal floor surface and external ground surface temperatures,

(ii) a sinusoidal flow along curving paths resulting from the annual swing of the smoothed external surface temperature about its mean value (the net flow over a year being zero),

(iii) flows in a vertical direction between the building interior and the floor resulting from heat inputs and temperature fluctuations (mainly diurnal) within the building.

3. The model representation of a building

The model has been written (3) as a suite of computer programs. Within the model a building is represented as spaces and walls. The physical spaces within factories are usually much larger than in other buildings, and so air movement and temperature variations within them require more detailed attention. Therefore, the model has been designed to allow the specification of more than one air volume (called a zone) within each physical space (or room). However, the model does not compute the movement of air between the zones within a room; this must be done separately and provided as input data.

Ventilation and heat inputs which depend upon the operating schedule of the building are given values for different periods of operation. These periods are given consecutively for each 24 hr period and each type of input independently. Each day may be the same, or seven different days can be described which are repeated in a weekly cycle.

A wide variety of heat loads can be accommodated including lights, occupants, equipment, as well as space heating and cooling. For all types, the radiant and convective components may be specified separately. The radiation from a source in one zone may strike surfaces in other zones within the same space; this may be specified. The output from space heating or cooling equipment varies in response to the thermostat settings given in the operating schedule.

In many factories, the level of natural lighting will be sufficient to obviate the need for artificial lighting for some of the time and so the model includes an option for automatic lighting control. When this is in force, the level of natural diffuse lighting inside the building is calculated from the diffuse sky radiation flux on the horizontal, and the artificial lighting input is set to zero if the natural lighting level exceeds the minimum required. When the natural level drops below the minimum, the artificial input is reset to its previous value.

The temperature in each zone may be allowed to float, or may be controlled. Two types of control are written into the model. One operates on air temperature, and may be used for heating or cooling. The other uses a combination of air and mean radiant temperatures and may be used only in the heating mode. Both types are idealised, and do not attempt to model the complete control characteristics of different types of heat emitter.

4. Weather data

The model is designed to use hourly values of weather data, including solar radiation and dry bulb temperature. In the majority of cases the data is obtained by selecting and extracting an appropriate period of weather from a database (9). Weather data may also be generated artificially, allowing the use of "design" conditions, or measured values from a validation experiment. Simulations using a complete year of weather data have been carried out. However, in order to compare the behaviour of different building designs, it was found preferable to extract from the complete weather record for a given site much shorter periods, of approximately one month duration, to represent specific weather types. Periods selected included the hottest and coldest in the record, spring and autumn averages, and periods of rapidly changing temperature.

5. Validation and sensitivity

Validation of the model using published experimental data (1,10) was carried out. Although the validation was satisfactory, it was not absolute, because the model is sensitive to the values chosen for input parameters which are not part of the measured data. This problem was explored by means of simulations carried out on a hypothetical but typical portal frame factory building, 50 m x 30 m on plan and 7.5 m high at the ridge. Results were highly complex (ref 3, chapter 7), but the main effects were:

1. using fixed recommended values (11) for the internal surface convection coefficients instead of the full equations substantially changed predicted temperatures (up to 3°C) and heating loads;
2. the temperature of the floor slab at the start of a simulation affected the results for several days;
3. assumptions concerning air movement within the space can significantly alter the predicted behaviour;
4. a model time step of 1 hour often produced large temperature discrepancies in the validation tests, whereas a time step of 20 minutes reduced these discrepancies by a factor of 4.

6. Factory simulation studies

Simulations were carried out on two typical factory designs the same size as used in the sensitivity analysis. Both were portal frame structures, but one was clad in thermally light materials, and the other in heavy materials. The simulations used a range of weather types selected from the database for Kew, London. Results were again complex, but some general trends did emerge. Firstly, the heavy building required more heating than the light building. The increase in energy depended on the type of heating, but was most affected by the type of weather. In the coldest weather the heavy building required between 6% and 7% more energy, whereas in average autumn weather the increase was between 15% and 26%, depending on the type of heating control. Secondly, in heat wave summer conditions the heavy building was much cooler, up to 10°C cooler on some days. Thirdly, it was found that the internal gains due to lighting and machinery can dominate the thermal behaviour. For a factory building built to current UK insulation standards with a high but not unusual level of internal gain, it was found that very little additional heat energy was required. In fact heating was only required during the pre-heat period before occupancy, and for a short time afterwards. In all but the coldest weather, the set point was exceeded for most of the working day, often by a considerable margin. Fourthly, it was found that an automatic control of the lighting had a very large effect, reducing the daily average lighting energy consumption over the heating season from 270 kW hr per day for the uncontrolled case, to 105 kW hr per day for the automatic case. Even greater savings were predicted for the summer season.

7. Conclusions

The main conclusion is that a complex thermal building model such as the one described here may not provide accurate results unless careful attention is paid to the details of the modelling process. When the model uses a finite difference approximation to the heat conduction equation, it is necessary to ensure that the approximation scheme, the choice of time step, and the method of distributing nodes will all be satisfactory for the full range of building types and design parameters to which the model will be applied. Good performance with one type of problem does not imply equally good performance with all possible problems. It has been found that the simple implicit scheme with a 20 minute time-step, using the method of distributing the nodes described in section 3, is least likely to produce unacceptable errors, even though other schemes may be superior in specific cases.

The method of modelling surface heat transfer coefficients has also been found to be critical. The use of lumped coefficients, in which radiation and convection exchange at surfaces is combined, can sometimes create large errors. Therefore a general purpose model should treat radiation and convection at surfaces separately. However, in factory buildings, the possibility of stably stratified layers adjacent to horizontal surfaces makes the choice of convection coefficient difficult; the existence of such layers has been observed in recent model studies (12).

Apart from the modelling process, the predictions of the model are often sensitive to certain key input parameters, the values of which may not be well known. For example, although the model allows for both spatial and temporal variations in air infiltration and internal air movement, there is little data of this sort available. Also, the thermal capacity of the floor slab can distort the results for several days, and yet the best temperature to use at the start of a simulation is unlikely to be known.

Concerning the behaviour of factories themselves, it seems that in the UK climate, lightweight structures require slightly less winter heating energy than heavyweight structures. However, if there are high incidental heat gains within the factory, it is better to have a heavyweight structure to avoid summer overheating.

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AN ASSESSMENT OF MOTIVATION AND METHODS UNDERLYING ENERGY MANAGEMENT IN 22 COMMERCIAL BUILDINGS

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Introduction

During the last decade, the Energy Research Group at the Victoria University of Wellington School of Architecture has been investigating the energy consumption of the 1100 commercial buildings in the Wellington Central Business District (CBD) via a series of projects (1, 2, 3, 4). The results from one such project (2) indicated that significant reductions in energy consumption had occurred in a number of buildings. Interest was thus aroused in discovering the reasons for these reductions, the methods used to achieve them and whether they had been sustained; with a view to improving the energy (management) performance of commercial buildings in New Zealand.

Methodology

Buildings that achieved at least a 15% reduction in their overall energy consumption between 1977 and 1980 were identified, and it was decided to concentrate on the bigger energy consumers rather than look at a large number of smaller consumers, as the former dominate the energy use of the CBD (20% of the buildings use nearly 80% of the energy consumed). The final sample of twenty-two comprised those buildings which initially used over 600 GJ/year, which achieved energy reductions of at least 15%, and for which a reasonably complete set of reliable data was available.

Having selected the group of twenty-two buildings, a two stage survey was conducted. The first stage involved visiting each building to ascertain its basic physical features, the types of energy consuming services installed, the nature and timing of any modifications during the 1977-1982 period, and the type and duration of occupancy of the building. In addition, the manager of each building was interviewed to obtain information on any energy conservation measures that had been carried out and to gain some understanding of the decision making processes involved. Notes on the results of this first stage were prepared, which included a summary of annual metered energy consumption and costs.

The second stage of the survey involved contacting the building managers to confirm that the data and notes were a correct interpretation of events during the 1977-1982 period and to probe further into the methods by which reductions in energy use and/or costs had been achieved, and the motivation behind them. In other words, to investigate the management processes involved in any decisions related to energy consumption and conservation.

Classification of Energy Management Processes

In terms of the energy management processes involved in these buildings, two main categories emerged, each of which was divisible into two levels. The first category was the ENERGY MANAGEMENT DECISION LEVEL which was divided into TOP MANAGEMENT and MIDDLE MANAGEMENT decision levels. The 'absolute' level of top management varied from building to building, but analysis indicated top management involvement with the energy management decision making processes of thirteen of the buildings. Middle management decisions had been involved in six of the buildings with top management being unaware, disinterested, unsupportive or otherwise not directly involved. In the remaining three buildings the reductions were not due to energy management initiatives of top or middle management, but changes in building use - they will not be considered further in this paper.

The second category involved the DIVISION OF RESPONSIBILITY FOR ENERGY COSTS, split here into SINGLE RESPONSIBILITY and DIVIDED RESPONSIBILITY. Single responsibility implied that a single organisation paid directly for ALL THE ENERGY consumed in the building. Ten of the buildings fell under this heading and these included offices, hotels and retail premises. Divided responsibility was where one organisation paid directly for CENTRAL BUILDING SERVICES, while another (or others) paid directly for TENANT SERVICES. Nine of the twenty-two buildings came under this heading, with responsibility for energy consumption divided between central and tenant services. The proportion of energy costs attributable to tenant services ranged from 16% to 62% of the whole building costs and averaged around 40%.

The overall classification of the 19 buildings is presented in Table 1. While the number of buildings in each group is relatively small and one should not read too much significance into the percentage savings, some interesting trends are indicated by the figures.

It will be seen that the average percentage cost saving for all 19 buildings is just over 20%, and this did not seem to vary significantly with level of management or division of responsibility. However, in buildings with divided responsibilities, it was found that the cost of tenant services had increased by one-third, no matter the energy management decision level. In the case of the central services, on the other hand, average cost savings of 47.2% were found for the six buildings where top management decisions were involved, and 25.1% savings for those three with middle management involvement only. In other words, where the metering was such as to allow the separation of central and tenant services, the impact of energy management by the building owner is clearly revealed.

Having classified the buildings from an energy management point of view and given an overview of the savings achieved between 1977 and 1982, each of the groups will now be examined in more detail.

ENERGY MANAGEMENT DECISION LEVEL	RESPONSIBILITY FOR ENERGY CONSUMPTION: BUILDINGS WITH SINGLE RESPONSIBILITY		BUILDINGS WITH DIVIDED RESPONSIBILITY				AVERAGE SAVINGS
	BLDG	COST SAVINGS %	BLDG	COST SAVINGS % Whole Bldg	Central Services	Tenant Services	
TOP MANAGEMENT	1.1	26.9	2.1	26.6	57.5	44.9*	
	1.2	10.5	2.2	19.8	25.8	39.9*	
	1.3	20.4	2.3	21.7	49.0	17.4*	
	1.4	15.4	2.4	55.6	62.8	21.8*	
	1.5	2.7	2.5	39.0	58.5	21.2*	
	1.6	30.7	2.6	4.7*	29.7	55.0*	
	1.7	33.8					
	average	20.1		26.3	47.2	33.4*	21.0
MIDDLE MANAGEMENT	3.1	3.2*	4.1	25.4	35.1	4.4	
	3.2	51.3	4.2	1.3*	8.0	73.0*	
	3.3	13.1	4.3	16.8	32.3	35.4*	
	average	20.4		13.6	25.1	34.7*	17.0
AVERAGE SAVINGS		20.1		22.1	40.0	33.8	21.1

Table 1 : Classification of the Survey Buildings by Energy Management Decision Level and Responsibility for Energy Consumption, together with the corresponding percentage cost savings comparison between 1977 and 1982.

NOTES (i) Cost savings are given in terms of 1982 energy prices and are calculated as follows:

$$\left(\frac{1977 - 1982}{1977}\right) \times 100 \text{ percent}$$

(ii) A percentage cost increase is identified by *

Group 1 Buildings : Top Management/Single Responsibility

The seven buildings of this group housed private companies (1.4, 1.6 and 1.7), hotels (1.2 and 1.3) and government departments (1.1 and 1.5)(see Table 1). It was found that the cost of energy was the prime motivating factor for the private companies and hotels, while conservation of energy (oil and electricity) lay behind the efforts made by the two government departments.

Top management 'support' took many forms. It could be simply the expectation of middle management that any economic measures likely to reduce costs (the fact that they might relate to energy consumption was incidental) would receive the support of top management. It sometimes took the form of top-down directives (both energy use and energy cost related), some with no effective feedback mechanisms, others with excellent monitoring and control procedures.

Of the technical methods which resulted in reduced energy costs, conversion of the boilers from oil to gas firing and adjustment of the running hours of the boiler were by far the most popular and most lastingly effective.

While most effort appears to have been directed at central heating systems, attempts were also made to reduce the consumption of electricity. These ranged from exhorting staff to switch off lights and appliances when not in use, to reducing fan and chiller running hours. It is always difficult to assess the outcome of such measures, given that these loads were not separately metered. However, in general, electricity use was not seen to be readily manageable.

Awareness campaigns had been tried in four cases but these had mostly lapsed. Energy monitoring was carried out in two buildings (1.1 and 1.3) as part of the routine budgeting and cost allocation procedures. It may be relevant to note that these two had the highest cost savings of the seven. A monitoring programme was also instituted in Building 1.5 but this had lapsed due, it would seem, to lack of feedback from top management to those doing the monitoring.

Group 2 Buildings : Top Management/Divided Responsibility

For these six buildings, it was possible to distinguish between central services and tenant services energy costs. It should be noted that while the average whole building savings amounted to some 26.3% and major savings (averaging 47.2%) had been made in central services energy costs, tenant services energy costs had INCREASED significantly in every case (ranging from 17.4 to 55.0%). The predominant activity in all six cases was private administration and all but one of the buildings were under the care of the property division of a (different) company which owned and operated other buildings too.

As far as the management of central services is concerned, it is clear that considerable experience has been gained in relation to the operation of central heating systems. Dissemination of that experience would be useful to other building managers as the methods used are not very complex. In this connection, it would be desirable to have typical or target figures available, especially for the owners of single buildings who may not have a basis for comparison of their energy consumption data. This is being addressed in New Zealand (5) and is a matter of concern in other countries too (6). In addition, more attention should be directed towards testing and publicising methods for reducing energy costs in cooling and HWS systems; and to ensuring that energy efficiency is considered when it is time to replace a boiler or heating system, or any other major piece of energy consuming equipment.

The management of tenant services seems to have been neglected as an area of potential energy conservation. There is a need for the development of management systems appropriate to this area, whether responsibility for energy consumption is single or divided. The 33% increase in energy use for tenant services compares poorly with the 40% reduction for central services in the subset of 9 buildings for which such data were available. Energy conservation awareness campaigns need very careful scrutiny before being applied to building occupants; poorly run campaigns can have considerable short term nuisance value and will adversely affect motivation for further energy management activities.

Conclusions

Looking to the future, there are several actions which can be expected to improve the energy (management) performance of commercial buildings. Some of these are based on the results of this study, others are simply reinforced by some of the findings, still others are related to the gaps in our knowledge revealed by the study.

The main methods used to save on energy costs in these buildings were straightforward to apply from a technical point of view and conceptually simple from a management viewpoint. This information could be disseminated more widely, with particular emphasis on the cost savings potential, to encourage other building owners and managers to follow suit. Coupled with this, and aimed at those already active in the field as well as those new to it, would be guidance on the nature and frequency of energy data collection needed to provide information for management purposes, and pointers to methods of saving energy in the operation of equipment other than heating systems. Given the apparently slower pace with which some measures were adopted in the 'middle management' group of buildings there is a need to provide further guidance on how a convincing case should be presented to top management.

Judging from the results, the management of tenant services energy costs seems an almost totally neglected area. Much more thought needs to be put into means of saving energy in this area - ranging from energy criteria for the selection of a building or space to rent, to the management of energy costs in use. An almost inevitable outcome of this will be the need for more judicious energy monitoring by management; not just general energy conservation campaigns directed towards the occupants which have no chance of achieving lasting savings.

Taken together, the 1979/80 oil restrictions and sharp price rises, plus energy conservation campaigns at that time, acted as a catalyst to some of the energy cost savings measures undertaken. New 'catalysts', appropriate to the current situation must now be found. Publicising actual energy cost savings in a range of buildings would go a long way in this area.

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