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# AIR INFILTRATION IN THE U.K. AND ITS IMPACT ON THE THERMAL ENVIRONMENT

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## ABSTRACT

The mechanisms and sources by which air infiltration occurs in dwellings are briefly described. Examples are given of adventitious openings to illustrate the wide range of sizes which occur in U.K. dwellings. Leakage rates through windows and through houses are compared with European standards to illustrate the values that can occur in U.K. houses. The importance of infiltration to both natural ventilation and mechanical ventilation is discussed. Before mechanical ventilation can be satisfactorily installed, measures to minimise adventitious openings are required. Example are given of the ways infiltration can adversely affect the thermal environment in well insulated dwellings. In such dwellings problems could be encountered with draughts and with the sizing of domestic heating boilers and radiators.

The general conclusion is made that in future housing much more attention should be paid to infiltration through adventitious openings. This should include the possibility of improving building construction to minimise infiltration. The relative merits of providing ventilation by infiltration, purpose-provided openings or by mechanical systems need to be assessed.

## 1. INTRODUCTION

As a result of a desire to economise in the use of energy in the domestic sector, various energy conservation measures have been taken in all countries where, because of climatic reasons, substantial amounts of fuel are required to heat homes. Top priority has, almost everywhere, been given to the application of additional insulation. In the United Kingdom revised Building Regulations(1) have been introduced and houses built to this standard show a significant drop in the design heat loss. Some houses are already being built with even a higher degree of insulation(2).

One-family houses are the predominant form of housing in the U.K., contributing 78%(3) of the total number of dwellings, and it is therefore evident that their energy performance will be the key to any substantial saving in the domestic sector. The application of further insulation to the structure of the house has resulted in the relative growth in importance of the ventilation heat loss as a fraction of the total, rising from crica 20% to nearly a half of the total design heat requirement(4). Any future energy saving measures will, inevitably, consider ways of minimising the ventilation component, but before any such measures are taken careful consideration will have to be given to whether they are effective and even desirable.

The provision of fresh air is required for health and comfort reasons and the recommended minimum rates of fresh air supply for dwellings are given by British Standard Code of Practice CP3(5). Fresh air may also be required to maintain the safe and satisfactory operation of a fossil fuelled appliance. It has been shown that a supply of fresh air for the needs of the occupants is more than adequate for the safe operation of open flued gas appliances(6). However, there has been a growth in popularity of gas balanced flue appliances which do not need the provision of combustion air in the house.

The Watson House laboratories of the British Gas Corporation have undertaken an extensive research programme on all aspects of air infiltration in houses - its energy conservation potential, influence on space conditioning systems and its impact on the thermal environment. The research programme has covered field measurements, test house and wind tunnel experiments, theoretical analysis and subjective tests in a controlled temperature room. The applicability of Continental experience with mechanical ventilation systems has also been reviewed.

By means of some of our research results and the results of others, it is intended to illustrate in this paper the sources and mechanisms of infiltration and to give an insight into the problems that it may cause in future housing.

## 2. MECHANISMS OF NATURAL VENTILATION

Natural ventilation occurs as a result of pressure differences acting across openings in the structure of a dwelling. The openings can be divided into two types, i.e. purpose-provided and adventitious. Adventitious openings are simply all of the openings which are not purpose-provided. Infiltration, or adventitious ventilation, is that part of the natural ventilation which is due to the adventitious openings.

The pressure differences arise as a result of the action of the wind and the action of buoyancy. The wind generates a pressure distribution over the external surface of the dwelling and any buoyancy of air inside the dwelling modifies the internal pressure distribution.

Ventilation due to wind can be considered as two components, i.e. flow induced by the time-averaged pressures and flow induced by turbulent fluctuations in pressure. Of these two components the former is generally considered to be most important, but for dwellings which are sheltered from the wind by other buildings this may not be the case. Wind tunnel tests carried out at Watson House and elsewhere show that the flucuating component can be relatively large for certain wind directions.

Ventilation due to buoyancy is commonly called "stack effect" ventilation. This refers to the difference between the internal and external air temperatures of a heated house. Ventilation is also caused by flues attached to boilers which take their combustion air from the interior of the house. Although stack effect has in the past been considered important only for very tall buildings, recent evidence suggests that it is important for two-storey buildings. For example, flow visualisation carried out by Watson House in test houses has often shown that the predominant ventilation path for the air is to enter through the downstairs rooms and to exhaust through the upstairs rooms. This is what one would expect for stack effect ventilation.

It can be seen that natural ventilation of a dwelling is determined by meteorological conditions, the shape and situation of the dwelling and by the size and distribution of its open areas. Of these factors only the size and distribution of open areas are amenable to modification or design for the solution of problems associated with natural ventilation. Therefore only these factors are discussed in detail below. All of the factors are of course very important when one is concerned with prediction of ventilation. A prediction method has been developed at Watson House(7) on the basis of semi-empirical crack flow equations(8). This is currently being assessed against data obtained in a test house. Wind tunnel models have been used to obtain pressure distributions and also to investigate ventilation induced by wind turbulence. The prediction method is being used for studying general trends, guiding experimental work and for investigating the effects of such things as mechanical fans and weatherstripping (seling of cracks around doors and windows).

## 3. VENTILATION OPENINGS

Ventilation openings are of two basic types, i.e. purpose-provided and adventitious. Purpose-provided openings are fairly common in U.K. houses. Examples of these are openable windows, air vents in bathrooms, WC's and kitchens and air vents in brickwork to ventilate the space below suspended floors. Chimneys and flues also fall into this category. As their name implies purpose-provided openings are installed for a purpose, e.g. to prevent condensation, to remove odours, to supply combustion air. Such openings are, of course, desirable and necessary. Provided that these openings can be designed to give satisfactory ventilation, adventitious openings become unnecessary. Research has shown that the areas of adventitious openings in U.K. dwellings can be much larger than those of purpose-provided openings (Table 1) and also that a wide range of sizes of adventitious openings can occur with similar dwellings. Although problems such as draughts can occur with purpose-provided openings due to oversizing or poor siting, greater problems are posed by adventitious areas because they are at present an unpredictable quantity. Basically, it seems preferable to control the level of adventitious openings, even if this means an increase in purpose-provided openings, because the latter are easily controlled by the designer or architect. In practice, control of adventitious openings would mean reducing their size to a minimum. Some countries have already moved in this direction.

Adventitious openings have a wide variety of forms. Cracks between the moveable and fixed parts of windows and doors are the most well known. In houses with suspended floors, which are common in the U.K., the total area of the gaps between the floorboards can by very large. Less obvious, but not insignificant, are the background areas. The "background" area is the area which remains for the room when the doors and windows (and purpose-provided openings) have been sealed.

The results in Table 1 indicate the wide range of values of adventitious openings which occur in U.K. dwellings.

Another way of characterising adventitious openings is in terms of their leakiness, i.e. the rate at which air flows through them when a given pressure difference is applied across them. This technique has been adopted for specifying standards not only for components but also for whole buildings. It is interesting to look at some results of this technique in detail because they indicate large differences between European standards and what is achieved in practice.

TABLE 1 Range of Open Areas Measured in Six Dwellings

| ADVENTITIOUS OPENING | EFFECTIVE OPEN AREA, $cm^2$ | |
|---|---|---|
| | BEFORE WEATHERSTRIPPING | AFTER WEATHERSTRIPPING |
| Door | 38 - 210 | 3 - 45 |
| Window | 6 - 110 | 3 - 14 |
| Background (room with suspended floor) | 52 - 150 | - |
| Background (room with solid floor) | 25 - 62 | - |

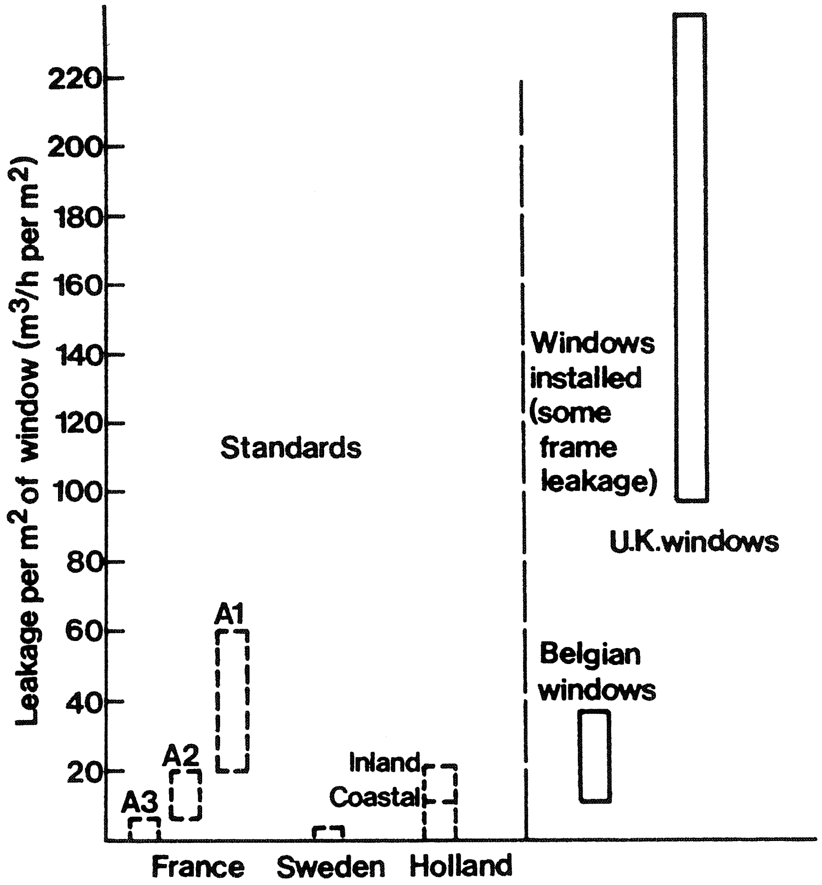

FIG. 1 Leakage through windows at 100 Pa. Comparison between measurements and standards.

Fig. 1 shows the leakage (per $m^2$ of window) through windows with a pressure difference of 100 Pa. The dashed lines show classes of windows as defined by French(11), Dutch and Swedish(9) standards.

The solid lines show the approximate range of values obtained from measurements made on windows in several Belgian houses(12) and in a house which has been investigated by Watson House(7). Fig. 2 is a view of the house.

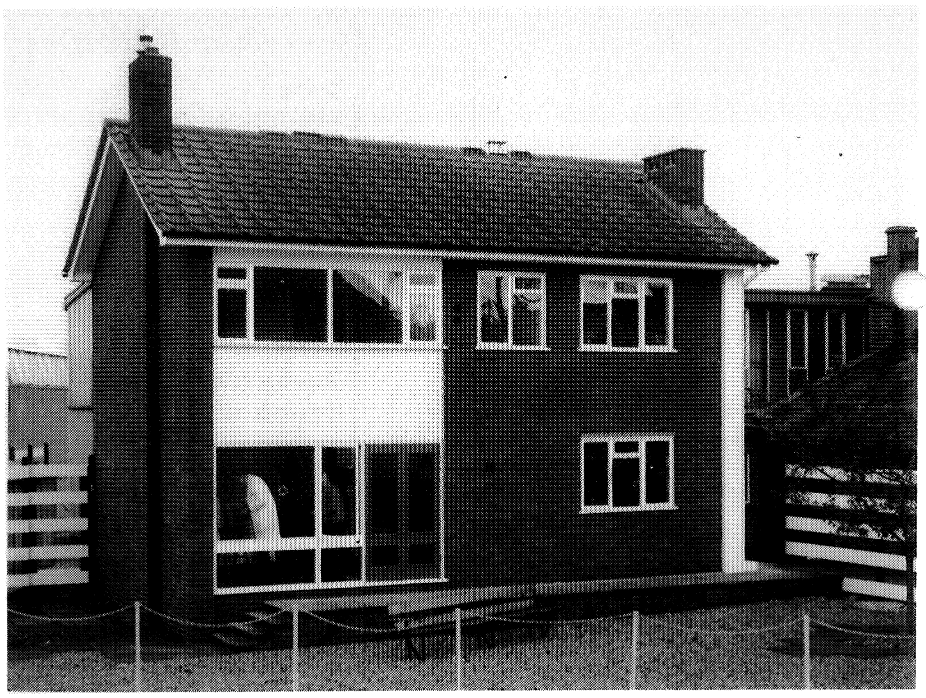

FIG. 2 View of BGC test house.

Fig. 3 shows leakage values for complete houses in terms of the number of air changes per hour (i.e. ventilation rate divided by house volume) at a pressure difference of 50 Pa. Values obtained from tests on one of the Belgian houses and the U.K. house are compared with recent Swedish standards.

The main implications from Figs. 1 and 3 is that practical U.K. house construction gives adventitious openings which are much larger than those specified in recent continental standards. Although data for only one U.K. house is shown in the figures, comparison with other data(13) indicates that it is not untypical of U.K. dwellings.

The differences between the Belgian and U.K. houses are interesting and it would not be surprising to find that U.K. houses are generally more leaky than their

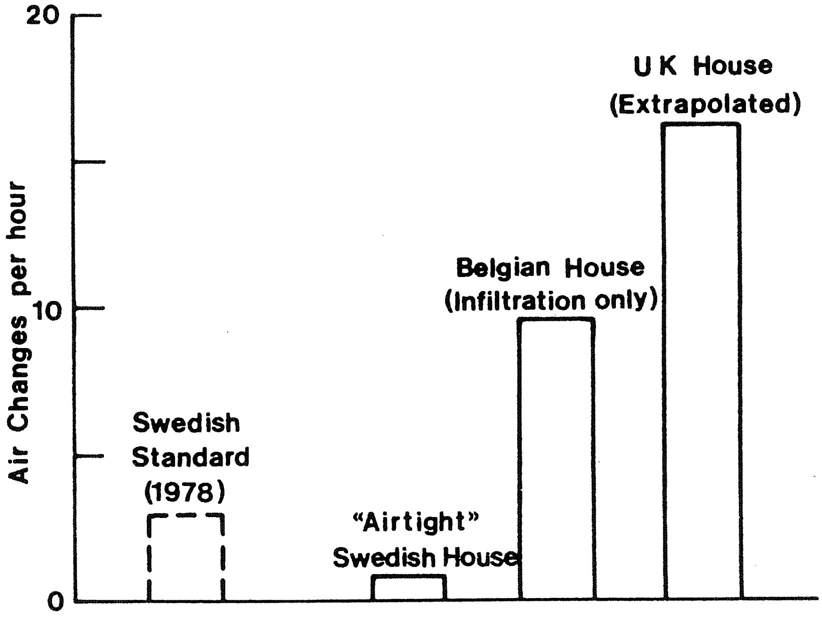

FIG. 3 Leakage of houses at 50 Pa. Comparison between measurements and standards.

European counterparts, because of the different construction techniques employed in the various countries. However, no extensive studies appear to have been made in this field.

## 4. NATURAL VENTILATION RATES

Since the driving forces of natural ventilation are meteorological it is obvious that a constant ventilation rate cannot be achieved. Thus, even if a standard ventilation rate for a given dwelling were specified, deviations from this rate must be expected. These deviations can be large and lead to the problems of comfort and energy losses described below.

An example of the size of these variations is given by measurements made in a detached house (Fig. 2) by British Gas. The amount of air entering the house has been estimated from simultaneous tracer gas measurements in the rooms(7) and the preliminary results are given in Fig. 4 as air change rate against the average wind speed at the time of the tests. Note that virtually all of the values of air change rate lie above 0.5 $h^{-1}$. The lowest value obtained occurred at a wind speed of 2.3 m/s with a negligible internal/

external temperature difference. Although it is theoretically possible for the air change rate to equal zero, this is unlikely to occur in practice. During the heating season when the house is heated, the air change rate is probably unlikely to fall below 0.5 $h^{-1}$. Values more than twice as large as this will occur at high wind speeds and/or low external temperatures. It is under these conditions that problems with comfort and energy losses are likely to be encountered. Also, it must be remembered that the way in which the fresh air enters is also important and this can be significantly altered by a change of wind direction.

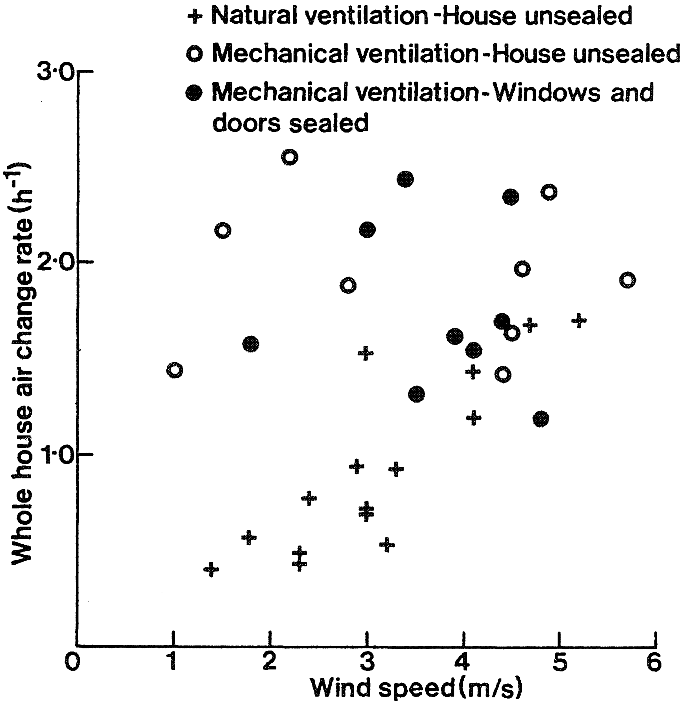

FIG. 4 Natural and mechanical ventilation rates in BGC test house (preliminary tests)

The problems arising from the variations in magnitude and direction of natural ventilation can in theory be solved by adopting mechanical ventilation. However, the solution is not as simple as it might at first appear. As well as installing the mechanical systems it seems that additional measures to seal the house will be needed and this will add to the cost of the installation. Support for this statement can be seen in (12) and also from recent measurements made in the test house by Watson House. The house is equipped with three mechanical systems, i.e. extract, supply, extract plus supply. Fig. 4 shows the air change rates obtained with the house in two conditions. The first condition is the same as that used for the natural ventilation tests. For the second condition, the windows and external doors were completely sealed (one external door was partially sealed). Comparison of these results with the natural ventilation rates shows that the installation of mechanical ventilation alone increases the ventilation rate substantially. After the application of the sealing the increase is smaller, but the ventilation rates with the mechanical systems are still generally higher than those for the unsealed house with natural ventilation. The reason for this is that sealing the windows and doors does not sufficiently reduce the total effective open area of the house (as can be judged from Table 1). The contribution of background openings to this total is significant. Only by reducing the total effective open area to a small value, such that the mechanical systems generate a large pressure in the house, can the ventilation rate by made independent of wind speed and external temperature. At these relatively high pressures it would be essential that a very low total effective open area be achieved, otherwise a ventilation rate above the optimum would occur. This would require extreme sealing measures and the enforcement of stringent standards for building construction. A very good example of this is the recent work being carried out in Sweden(9) on sealing houses with polythene sheet. Although successful in Sweden, it is doubtful whether such extreme measures would be acceptable on grounds of cost for new houses in the U.K.

The leakage standard which has been adopted for these houses is the one labelled "airtight" in Fig. 3. With such a tight construction it becomes important for the ventilation rate given by the mechanical system to be correctly set. This means regulating not only the magnitude but also the direction of the ventilation flows for winter and summer conditions. The possibility of having a ventilation rate which is too low becomes quite likely and problems with condensation are probable. An air change rate of 0.5 $h^{-1}$ has been chosen for the houses in (9) and this value seems to be readily achievable by infiltration along (see Fig. 4). It is therefore debatable whether the potential advantages of the Swedish system could be justified on cost grounds in the U.K. where the winter climate is more moderate and ventilation heat losses smaller. In the U.K. it might be preferable to minimise the adventitious openings in new dwellings and accept the small degree of control offered by purpose-provided openings. Further research is needed to answer this question.

## 5. IMPACT OF INFILTRATION ON DESIGN & COMFORT REQUIREMENTS

It is obvious that the total volume of fresh air entering a dwelling will influence the magnitude of the ventilation heat loss, but its flowpath through the dwelling and the way it is introduced into the living area are equally important. The way fresh air is introduced into the living area is one of the decisive factors of whether design thermal comfort criteria will prove acceptable to the occupants or if higher, and therefore wasteful of energy, temperatures will have to be accepted to combat local sources of discomfort. Air infiltration and especially its flowpath through the dwelling also influence the sizing of space conditioning systems.

### 5.1. Sizing of Central Plant and Emitters

Historically in the U.K., because of high heat loss through the fabric, the ventilation heat loss has constituted only a minor part of the total heat loss. Any fluctuation of the infiltration rate, due either to a change in the wind speed or its direction, did not unduly influence the performance of a usually oversized system. With the advent of higher levels of insulation, combined with a desire to limit the level of infiltration, the balance has changed and careful consideration will have to be given to the sizing of the central plant and emitters. The penalty of designing a system based on optimistic forecasts of low ventilation rates that, as has been shown, are difficult to achieve using contemporary U.K. construction methods, is severe.

Computer based studies carried out at Watson House(4) have shown that an inflow rate of 0.5 air changes per hour instead of a design rate of 0.2 air changes per hour will result in a decrease of temperature in a typical living room from 20°C to 17°C on a design day having a mean temperature of -1°C.

If houses are to be highly insulated but not "air tight" allowance in the sizing of heat emitters will have to be made for a relatively large fluctuating component of the heat loss as represented by the infiltration heat loss. Measurements in test houses and theoretical predictions(4) have shown that the flow of fresh air through a house is far from even, as is assumed in standard heat loss calculations. The largest fluctuations, i.e. a change in direction from inflow to outflow can occur quite rapidly and will, by definition, be of opposing direction in different rooms. The adoption of individual room temperature control is a likely solution to this problem.

The result is equally dramatic if low design infiltration rates are used in the calculation of the heat output. An optimistically sized system when subjected to one air change per hour(4) would have difficulty in attaining internal design temperatures even after 16 hours of plant operation on a design day.

## 5.2. Low Level Draughts

Low level draughts are usually associated with older, leaky and less insulated houses. A high degree of insulation, if not associated with "airtight" construction and controlled ventilation, could also be a cause of local discomfort due to low level draughts. In a thermally well insulated enclosure a cold air flow, generated by infiltration and augmented by convective currents from mainly single glazed windows, could be the dominant force governing room air movement patterns. Double glazing is difficult to justify economically in the U.K. climate. The heat emitter will be relatively much smaller, not covering the whole width of the window. For cost reasons, the now smaller emitter may be placed against one inside wall and thereby aggravate the situation.

In order to evaluate how low level draughts influence the subjective perception of the overall thermal environment, a series of controlled tests were conducted in a test facility at Watson House.

As a first step, to gain an appreciation of the conditions that are likely to occur in the field, measurements of temperature and velocity profiles were made in an occupied house. As an example, measurements in the living room on a mild day are shown in Fig. 5. The results indicate that there is a definite current of colder air up to a height of 0.3 m from the floor. The boundary between the current and the relatively still air is characterised by large low frequency fluctuations in the velocity of up to 0.35 m/s. The effect of having the curtains closed is to reduce the mean velocity of the cold current, but at the cost of having a less uniform temperature profile (compare profiles A1 and A2). In the centre of the room, velocity profiles were generally found to be similar to profile A2 but the temperature more uniform (profile B). Similar values were confirmed by measurements taken in a furnished test house. The conclusion that can be drawn from these results is that even in relatively mild climatic conditions, with the windows and doors weatherstripped, cold currents having velocities between 0.1 and 0.2 m/s and of temperatures between 17 and 19°C can be encountered at ankle height in well heated rooms (mean temperatures 21°C).

The controlled experiments were carried out in the experimental Controlled Temperature Room at Watson House. Conditioned air was distributed through three low level grilles so as to achieve a uniform current of air across the room up to a height of 0.3 m.

Two series of tests were undertaken. In the first series the effects of four draught temperatures (16, 18, 21 and 23°C) at a constant velocity of 0.2 m/s were investigated, and in the second three lower velocities (0.05, 0.1 and 0.15 m/s) at two temperatures (21 and 23°C) were used. For all of the tests the mean room temperature (air and globe) was kept at a nominal 23°C. In each series of tests twelve male

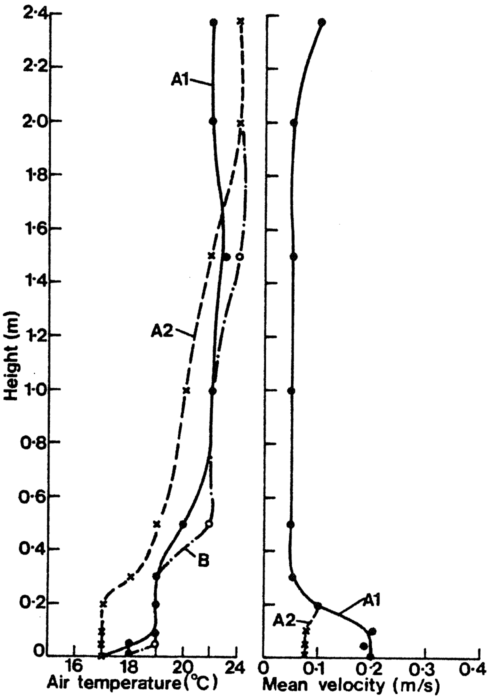

FIG. 5 Velocity and temperature profiles in a living room. External temperature 9°C, mean wind speed 3 m/s parallel with house, window and external door weather-stripped, mean radiator temperature 45°C (under window)
A1 - 0.5 m from door, curtain open
A2 - 0.5 m from door, curtain closed
B - centre of room, 1.75 m from window, curtain closed

and twelve female subjects, two at a time, were exposed to each test condition. The tests lasted one hour and the subjects were requested to wear similar clothing throughout the experiment. At the end of each session the subjects were asked to record their vote in response to a set of questions.

The environment around the feet was assessed on a seven point Bedford scale. The distribution of the "foot" vote for both series of tests is shown in Fig. 6. The distribution shows that, as expected, the proportion of votes of "comfortable" (vote 4) is greater the higher the draught temperature. Fig. 7 shows the calculated regression line relating the foot vote with the temperature of the simulated draught for the first series of tests. The graph indicates that to achieve optimum thermal comfort conditions (vote 4) at foot level for a draught velocity of 0.2 m/s men required a temperature of 24°C and women 26°C. The difference could probably be explained by a difference

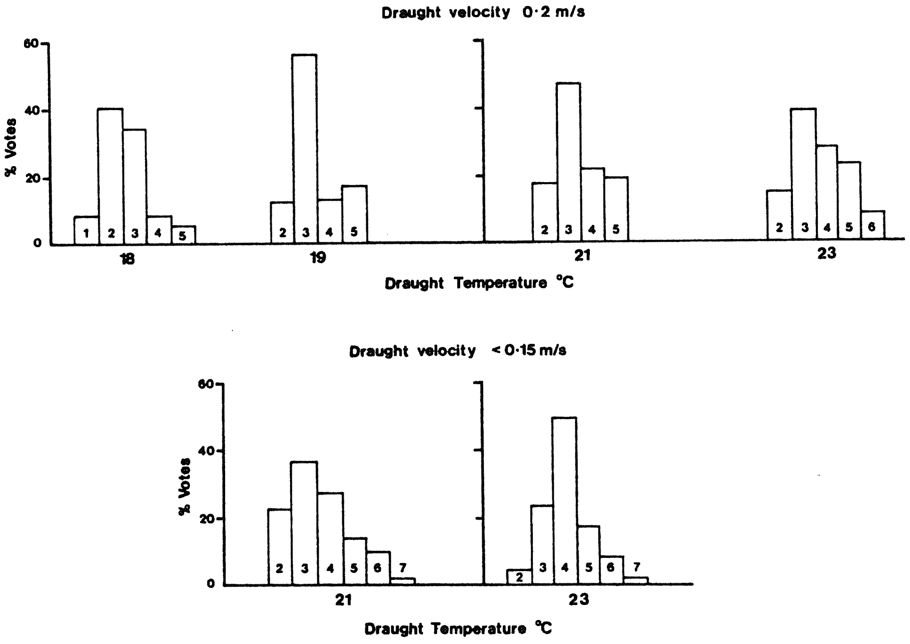

FIG. 6 Distribution of foot votes, Bedford scale, for different draught temperatures and velocities. Bedford scale: 1 - much too cool; 2 - too cool; 3 - comfortably cool; 4 - comfortable; 5 - comfortably warm; 6 - too warm; 7 - much too warm

in the clothing ensemble. For the second series of tests at lower velocities only slightly lower temperatures were obtained. Analysis of data of the second series of tests showed that, although the assessment of the environment around the feet depended more on temperature than velocity, even slight air movements around the feet could be a cause of discomfort at temperatures that would otherwise be considered within the comfort range.

The subjects were also asked to assess the overall thermal environment on a seven point Bedford scale. The room temperature, as previously mentioned, had been kept at a nominal value of 23°C globe temperature throughout the experiment. When the overall vote is plotted against the foot vote, see Fig. 8, it is apparent that the overall assessment is dependent on the conditions at foot level. These results show that although the greater part of the body was exposed to an optimum thermal environment, a local source of discomfort, low level draughts caused by infiltration and cold convective currents, can be a predominant

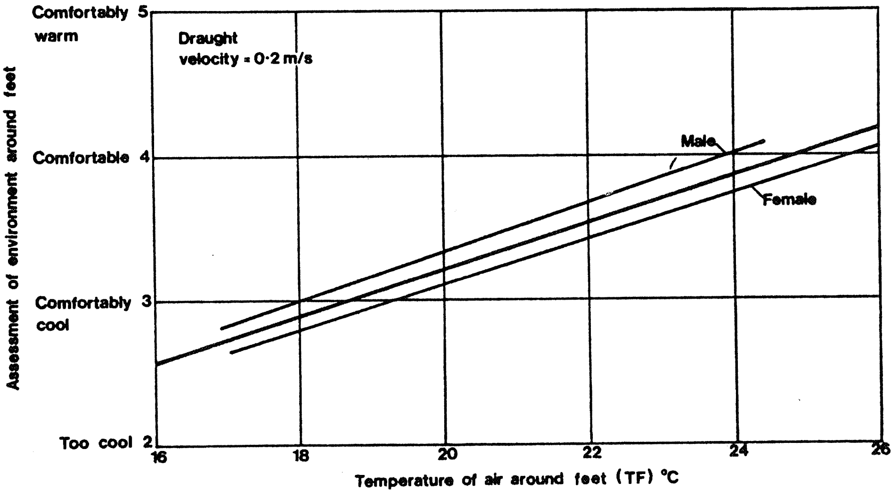

FIG. 7 Calculated regression line of foot vote against draught temperature. (R = 0.303, 93 degrees of freedom, significance level $p < .0005$)

factor influencing the assessment of the overall thermal environment, i.e. when feet are cold, the person will feel cold overall.

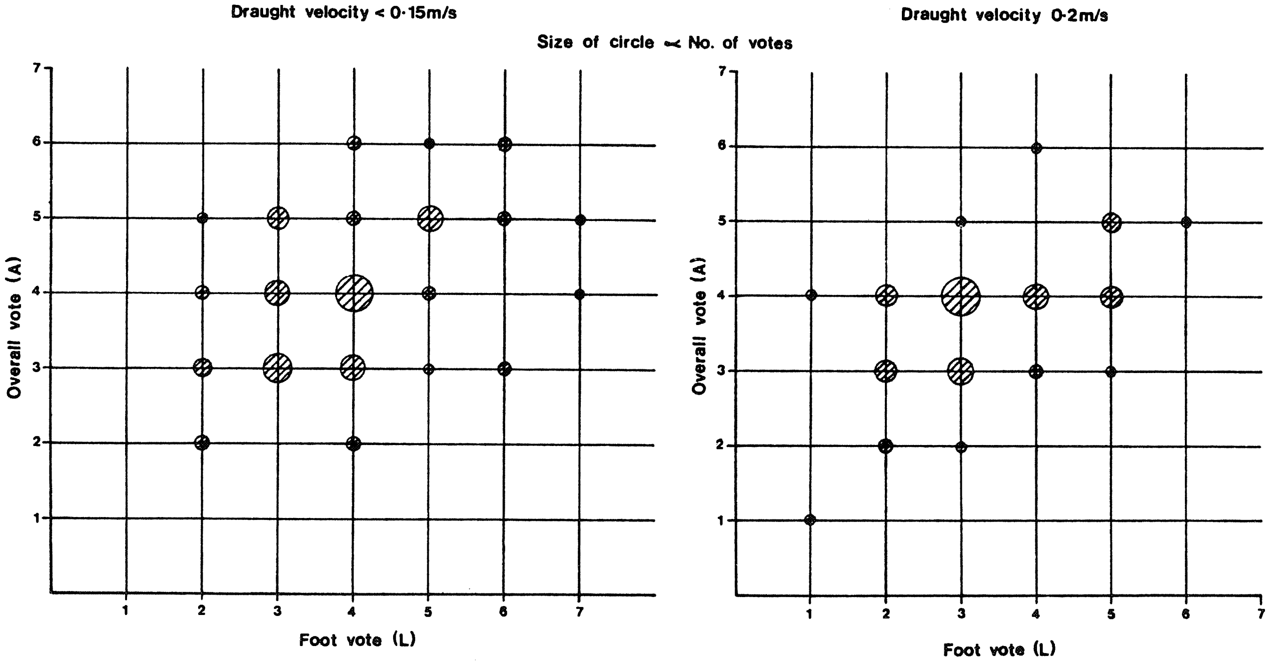

FIG. 8 A plot of overall vote against foot vote

## 5.3. <u>Operation of Ventilation/Warm Air Systems</u>

Low level draughts, as a source of local discomfort and therefore a potential source of excess energy consumption, may not automatically be entirely eliminated by the introduction of mechanical ventilation/warm air heating systems. One obvious source of draughts, referring to the results presented in the previous chapter, is the introduction of air into rooms at insufficient temperatures.

Ventilation/warm air heating systems in the U.K. are usually operated intermittently, either throughout the whole control range or at low load conditions of otherwise modulating systems. Intermittent air injection into rooms, i.e. on-off control of the supply fan, could result in discomfort due to the re-establishment of infiltration draughts during the "off" period of the control cycle. To combat discomfort during this period the occupants may take action by altering the thermostat setting and thereby both raising the temperature and shortening the "off" period. The critical factor governing the response of the occupants is the time required for the jet generated room air movement pattern to become established and to decay.

The study of intermittent air injection into rooms is being sponsored by British Gas Corporation at the Cranfield Institute of Technology. Preliminary studies of two-dimensional, isothermal, plane wall jets intermittently injected into a test chamber have been completed(14). Fig. 9 shows the jet growth and decay at a distance of 3.5 m from the aperture. As can be seen circa 60 seconds have to elapse before the jet has built up to steady state conditions. The decay is more rapid, requiring only 40 seconds to reach still conditions. Flow visualisation techniques have shown that the time for total room air movement to attain a steady state did not exceed 75 seconds. Although the time will vary with the shape, size, room furniture and will be influenced by convective currents generated by cold wall surfaces, radiators, etc. the preliminary results indicate that the interval that the supply fan can be "off" is relatively very short, if infiltration draughts are to be suppressed.

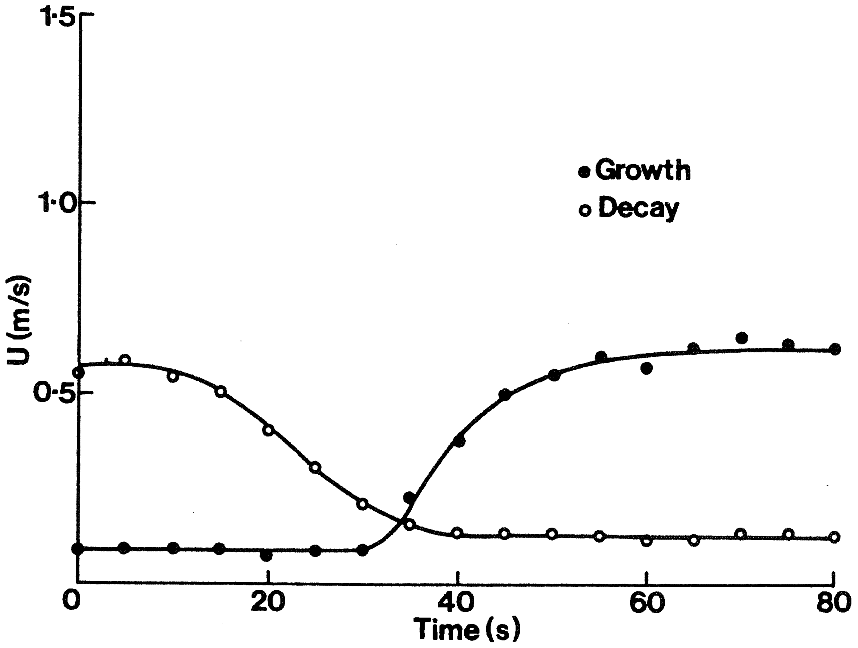

FIG. 9 Jet growth and decay of a two-dimensional, isothermal plane wall jet intermittently injected into a test chamber (4.8 x 2.45 x 2.45 m) at a rate of 8 air changes per hour

## 6. CONCLUSIONS

In future well-insulated dwellings more attention will have to be paid to infiltration. The heat loss associated with it constitutes a large fluctuating component of the total heat loss. Any underestimate of the magnitude of the infiltration rate in the sizing of heat emitters and central plant could lead to the failure of space conditioning systems to achieve design conditions.

Low level draughts are caused by infiltration and experiments have shown that even slight air movements around the feet (up to 0.2 m/s) could be a cause of discomfort at draught temperatures that would otherwise be considered within the comfort range. The experiments also indicate that the assessment of the overall environment is dependent on conditions at foot level. Failure to suppress low-level draughts can therefore be a cause of excess energy usage. If low-level draughts are to be suppressed by mechanical ventilation/warm air systems operating intermittently, the systems should operate with short "off" periods.

In some countries standards have already been introduced to reduce infiltration. If similar standards were introduced into the U.K., measurements of leakage rates in present-day houses indicate that construction techniques would have to be considerably improved to satisfy them. With mechanical ventilation systems such measures have to be adopted to minimise adventitious openings, as illustrated by recent developments in Sweden with "air-tight" houses. These measures might not be acceptable on cost grounds in more moderate climates and this casts doubt on the use of mechanical ventilation systems in future housing. A cheaper, but less effective alternative is to minimise the adventitious openings and substitute purpose-provided openings where necessary. This removes the uncertainties about the size of adventitious openings and gives some degree of control over the magnitude of the natural ventilation rate and the places at which air enters. The value of this needs to be assessed.

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