ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING
ACCEPTABLE INDOOR AIR QUALITY

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NATURAL VENTILATION IN THE UK AND SOME CONSIDERATIONS FOR ENERGY EFFICIENT DESIGN

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1. INTRODUCTION

There are approximately 19 million dwellings in the UK and virtually all of them are naturally ventilated. Some of them are equipped with extract fans for intermittent use, but even then most of the ventilation is natural . In the past, dwellings have not been designed in detail for natural ventilation. All that has mainly been required is that they should satisfy certain very generalised specifications (e.g. the provision of openable windows), and this has proved to be a generally satisfactory procedure. However, in future low-energy dwellings excessive ventilation rates are particularly undesirable, because they negate the benefits arising from thermal insulation. On the other hand, it is equally important that ventilation rates are not reduced too far. To satisfy these two conflicting needs, means that a ventilation system should be designed much more closely than has been necessary, or possible, in the past.

Basically, the aim is to achieve an "energy-efficient" system. In the light of recent research, the present paper discusses the potential for achieving this aim by improving design procedures for natural ventilation. The paper falls into four main parts.

Section 2 considers ventilation requirements and the meaning of the term "energy-efficient" ventilation. Both of these topics are of fundamental importance to any design procedure.

Section 3 discusses natural and mechanical ventilation systems. This is done, because natural ventilation is often compared unfavourably with purpose-built mechanical systems. It is argued that such comparisons can be misleading, unless all aspects are considered.

The basic characteristics of natural ventilation are summarised in Section 4. Research in recent years has led to a considerable increase in knowledge of ventilation. This enables the main problems to be identified and indicates ways of improving design procedures.

Section 5 discusses the main aims of design and possible ways of achieving them.

Finally, there is a short summary of the main conclusions.

2. VENTILATION REQUIREMENTS

Probably the most recent concensus of views concerning ventilation requirements in the UK is incorporated in the British Standard 5925 (Ref. 1). This document gives a comprehensive summary of the reasons why ventilation is needed and describes methods for calculating ventilation requirements (i.e. air flow rates). At present, the largest requirements in dwellings will often be associated with the control of internal humidity or the dilution and removal of odours. This means that the required ventilation rates will depend on such factors as level of occupancy and domestic activities,and they will therefore change with time. This is a very important point, when defining the energy efficiency of ventilation (see below) and when considering practical design objectives.

When designing a mechanical ventilation system, one considers the requirements to be fixed values, since the purpose of current systems is to keep the whole-house ventilation rate and the room air change rates constant (some systems do have "boost" settings). Similarly when sizing permanent air vents for a natural ventilation design, one would consider only one flow rate for each room, because a vent of fixed dimensions can only be sized for one condition.

Such procedures are not really consistent with a varying ventilation requirement, but in practical terms they are probably unavoidable. However they do raise the question of whether a highly accurate design procedure is justifiable, when the actual ventilation requirements have to be expressed in a very simplified form.

This in turn raises the question as to whether more attention should be paid to the variable control of ventilation when seeking an "energy-efficient" system.

2.1. Energy-Efficient ventilation

To define the energy efficiency of a ventilation system is not easy, if only because the energy loss which one wishes to reduce is not totally involved in actually driving the ventilation process. However a loose definition is suggested in the following, because it illustrates in a concise way the basic elements of an efficient system.

A perfect system would be one in which the actual ventilation rate, R_A, is equal to the required ventilation rate, R_R, at all times i.e. the reduction of energy losses by reducing ventilation below the required levels is not desirable and therefore should be interpreted as a reduced energy efficiency, η_E. Accordingly, η_E can be loosely defined as

$$\eta_E \equiv \left[1 - \frac{\int |R_A - R_R| \cdot dt}{\int R_R \cdot dt} \right] \cdot \left(\frac{\eta_v + \epsilon}{2} \right)$$

where time integrals are evaluated over the heating season, η_v is the ventilation efficiency and ϵ is the fraction of heat loss recovered. R_A and R_R are whole-house ventilation rates, because to a first approximation the heat loss will depend on these rather than room rates.

In the above definition, the term in square brackets means that maximum energy efficiency can only be achieved when the ventilation requirements are precisely satisfied. For a mechanical system which maintains R_A at a fixed value, the term will generally be less than unity because of variability in R_R.

For a natural ventilation system, there is the additional reason that R_A will also vary, due to weather and to occupant actions (e.g. opening windows). Ideally, the control exercised by the occupant should be such as to increase η_E by adjusting R_A to be closer to R_R. If the occupant exercises no control whatsoever, then the natural system is certain to be less efficient, because $\int |R_A-R_R|$ is certain to be larger. The first term in the definition is therefore associated with control, both as a result of design (the design aim might be to make the mean values of R_A and R_R equal) and as a result of occupant action.

The second element is the ventilation efficiency, ηv. This represents the fact that the effectiveness of a given air flow rate in, say, removing odours depends on where and how the air passes through the room. Since ventilation efficiency is related to room air movements it is a very complex subject (e.g see Ref. 2). One aim of increasing η_v is to reduce R_R and methods for calculating R_R may make implicit assumptions about ηv, e.g. the assumption of a perfectly-mixed atmosphere.

The third element in energy efficiency is represented by the term ϵ. Obviously if some of the ventilation heat loss can be recovered, the energy efficiency of the system will be increased. Indeed, if the system also recovers heat from a flue, then ϵ could be greater than unity.

Of the above three elements, the first is probably the most relevant to natural ventilation design, because it is the least difficult to tackle. The second element presents much harder theoretical problems. With natural ventilation it is difficult enough to predict the air flows entering a dwelling, let alone what happens to them inside. Regarding heat recovery, it is fair to say that this has little potential, although there is some scope for it with secondary glazing (Ref. 3).

Finally, on a less technical note, any system could not be considered energy-efficient in practice unless it was also cost-effective, or unless the cost could be offset against other benefits. This is an important point when considering mechanical ventilation systems.

3. COMPARISON OF NATURAL AND MECHANICAL VENTILATION

In what follows, natural ventilation is taken to include cases where one or more individual extract fans operate intermittently. Such cases are probably fairly common in the UK and the fans can be considered as an alternative means of control to opening windows. Mechanical ventilation is taken to mean ducted systems which are intended to satisfy the requirements of the whole dwelling and which operate more or less continuously.

The main features of natural ventilation are:-

- low initial cost and maintenance costs
- mechanically simple
- widely accepted (in the UK)
- partly controllable by occupants
- unavoidable variations in whole-house rates and particularly room rates due to weather
- difficult to predict ventilation
- heat recovery not feasible

Roughly speaking the main features of mechanical ventilation are the opposite of the above. In addition, their proper operation depends on the construction of the dwelling being relatively tight. There are three basic types of mechanical systems i.e. supply, extract and balanced. The first two are the least expensive (particularly if they are part of the heating system, as in one UK warm air system) and they require less tight dwellings for proper operation (Ref. 4). However balanced systems are more easily adapted for heat recovery and allow room ventilation rates to be fixed more closely.

Purely from the viewpoint of theoretical energy-efficiency, balanced mechanical systems are more promising than natural ventilation. However their initial cost is very high and in the moderate UK climate their cost-effectiveness is doubtful (even when the expense of making the dwelling airtight is excluded), because the time taken to recover the costs of the system from the energy savings may be unacceptably long. Now, as noted in Ref.4, the basis for estimating these savings is the energy consumption of naturally ventilated dwellings. In Ref. 5 it is pointed out that with an average natural ventilation rate of 1 per hour, the balanced system does not appear to be an attractive investment. It is then suggested however, that in practice natural ventilation rates may be much larger than this due to excessive window-opening, and balanced systems may be cost-effective. This argument remains to be proven, and as will be mentioned below the experimental data on which the argument is partly based may give a pessimistic view of the effects of open windows.

Nevertheless the argument is important in the present context, because it gives a further reason for the designer to consider the control aspects of natural ventilation. In fact, if natural ventilation design can achieve average air change rates of about 1 per hour, one of the justifications for balanced mechanical systems becomes very doubtful. There are however other reasons why a mechanical system might be chosen in preference to natural ventilation. The two systems are virtually opposites and differ fundamentally in approach i.e. mechanical systems attempt to remove the need for occupant control, whereas it is implicit in natural systems. Each system has its own advantages and disadvantages, and the choice of system is likely to be decided after consideration of many different factors.

4. CHARACTERISTICS OF NATURAL VENTILATION

The inherent characteristic of natural ventilation is its variability. This has its origins in many factors, but it is convenient to summarise them here under the somewhat loose but familiar headings of leakage, weather and window-opening. Results obtained with the measurement technique ("Autovent", Ref 6)and the theoretical model ("Vent", Ref.13) developed by British gas will be used for illustration.

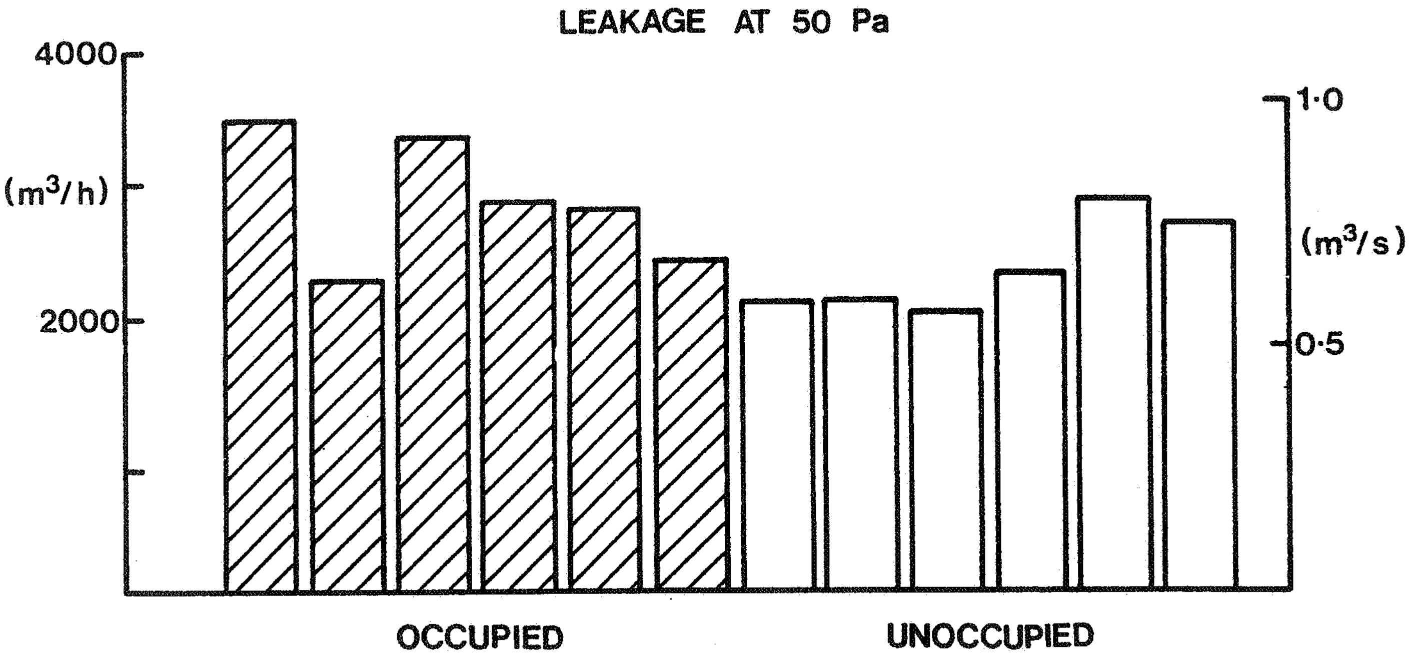
4.1 Leakage

The leakage of a dwelling (i.e. the flow rate required to pressurise the dwelling to a specified value, often 50 Pa) is likely to be one of the most important parameters in design.

The openings which contribute to the whole-house leakage can be divided into three main types (Ref. 6) - purpose-provided, component, background leakage areas. Measurements in UK dwellings (eg. Ref. 7) suggest that the third type often makes the greatest contribution, at least at high pressures. This poses problems because background openings are difficult to identify and cannot easily be controlled by design, other than by trying to eliminate them completely. One result of this is that nominally identical dwellings can have different leakages. Figure 1 illustrates this with some recent data obtained in low-energy houses.

Another feature is that the leakage of a dwelling may increase during the early part of its life, possibly by a factor of two. Thereafter smaller seasonal variations may occur.

The above characteristics are related to the construction of the dwelling and may pose severe problems to the designer. There are also some rather more fundamental problems, about which relatively little is known.



LEAKAGES OF TWELVE NOMINALLY IDENTICAL DWELLINGS

FIG. 1

First it is quite likely that the leakage of a dwelling will be used as a basis for design, by relating it to ventilation rate and weather conditions. Several calculation methods of this type already exist. However leakages are of necessity generally measured at much higher pressures than those encountered with natural ventilation. It is therefore necessary to make assumptions about low-pressure leakage behaviour, and these assumptions may be a source of considerable error. It is not inconceivable (see Ref. 8) that two dwellings with the same leakage at high pressure (50 Pa) could have leakages at 2 Pa which differ by a factor of two. High pressure leakages therefore may not be a suitable basis for design. More information about leakage characteristics over the whole pressure range is needed so that the extent of the problem can be assessed. This presupposes the existence of a suitable measurement technique which, with the possible exception of that described in Ref. 9, remains to be developed.

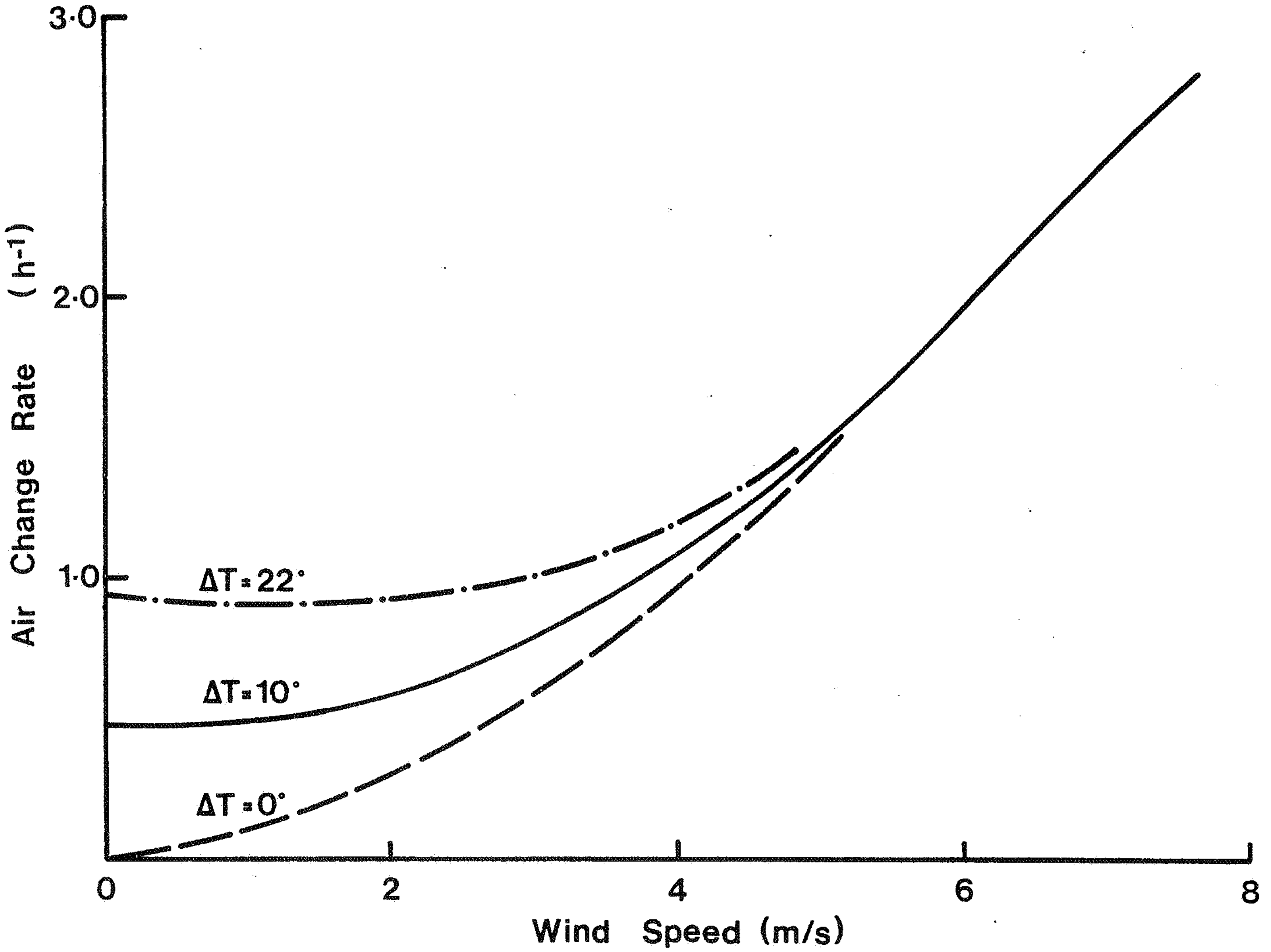
Another problem is posed by the distribution of leakage about the dwelling. Although techniques for measuring it have been developed (Ref. 6), little is known about the range of distributions likely to be encountered in practice. There is also uncertainty about how important it is. Theoretical calculations (Refs. 10 and 11) suggest that it could be significant e.g. two dwellings with identical leakages but very different distributions could have ventilation rates which differ by 50%. The influence on room rates is likely to be greater, and some experimental evidence of this can be seen in Ref. 12. Again, more information is needed about leakage distributions to assess the size of the problems. There is also a positive aspect to this, because by modifying the leakage distribution the influence of weather could be altered.

4.2 Weather

The driving forces of natural ventilation are the pressures generated by buoyancy and wind, which act on the openings distributed about the dwelling. Ventilation due to buoyancy alone is determined by the differences between internal and external temperatures. Ventilation due to wind alone is much more complex, since it depends on the speed and direction of the wind and the location and shape of the dwelling.

Design data concerning temperatures is much more readily available than it is for the wind parameters. It is fortunate therefore that buoyancy is often important in determining the ventilation of dwellings in the U.K. Not only is ventilation due to buoyancy less difficult to predict, the presence of buoyancy reduces the variability of ventilation arising from wind effects. Figure 2 illustrates these points with some predictions from our mathematical model for a detached house. Assuming that one can predict the whole-house ventilation rate with buoyancy alone (wind speed equal to zero), this prediction will be reasonably accurate for wind speeds up to about 3 m/s. Thus quite a wide range of weather conditions can be covered without any knowledge of wind parameters. This could prove to be a very valuable simplification for design purposes. Unfortunately it is likely to be less valid for terraced dwellings (where the openings are concentrated on two surfaces and high wind pressures could be encountered with winds perpendicular to the terrace), and it does not apply to room ventilation rates.

Wind effects are much more difficult to predict than buoyancy, because one needs to know the surface pressure distribution generated by the wind on the building and how this varies with wind direction. Another complicating factor is that for design purposes one needs to be able to relate the pressure distribution to a wind speed and direction for which meteorological records exist. At present such relationships have to be estimated from very limited data obtained from wind



INFLUENCE OF BUOYANCY ON WHOLE HOUSE AIR CHANGE RATES

FIG. 2

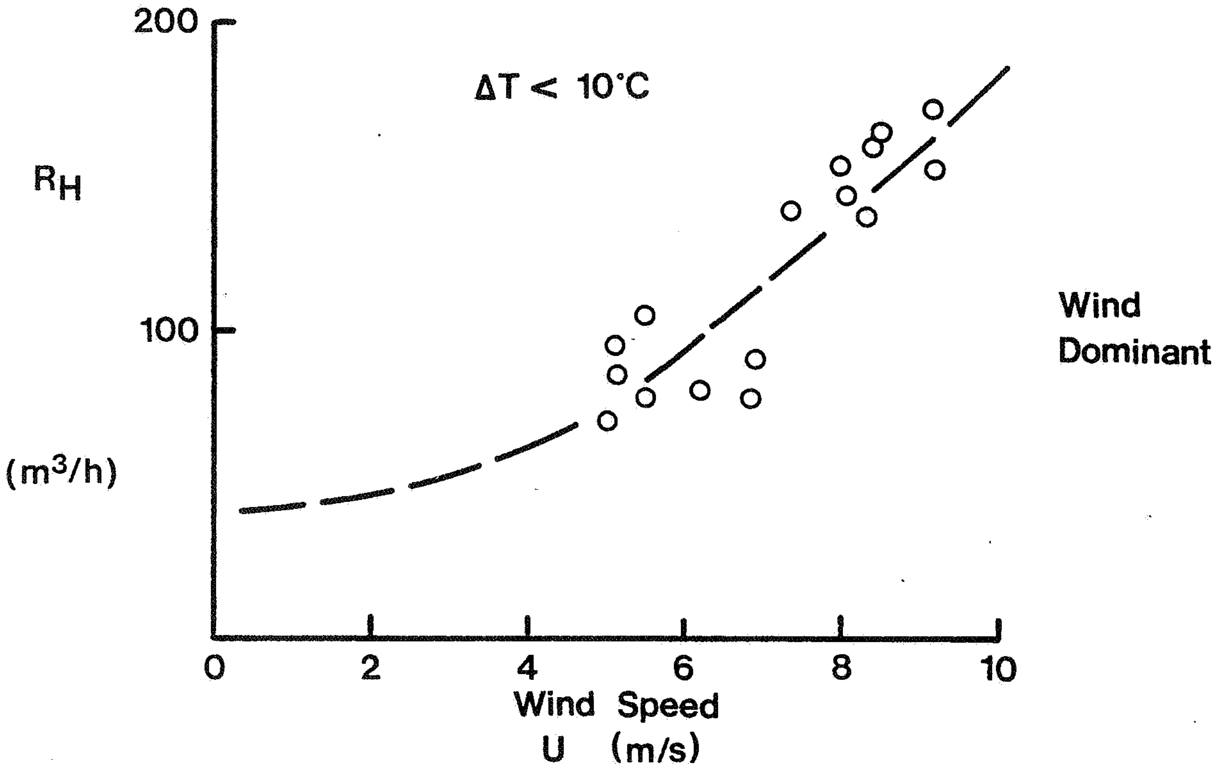
tunnel tests. There is a considerable amount of work which remains to be done on the wide range of dwelling shapes and arrangments which exist in practice. Indeed it is doubtful if all such combinations could ever be covered. For these and other reasons, there is an incentive to the designer to minimise the effects of wind.

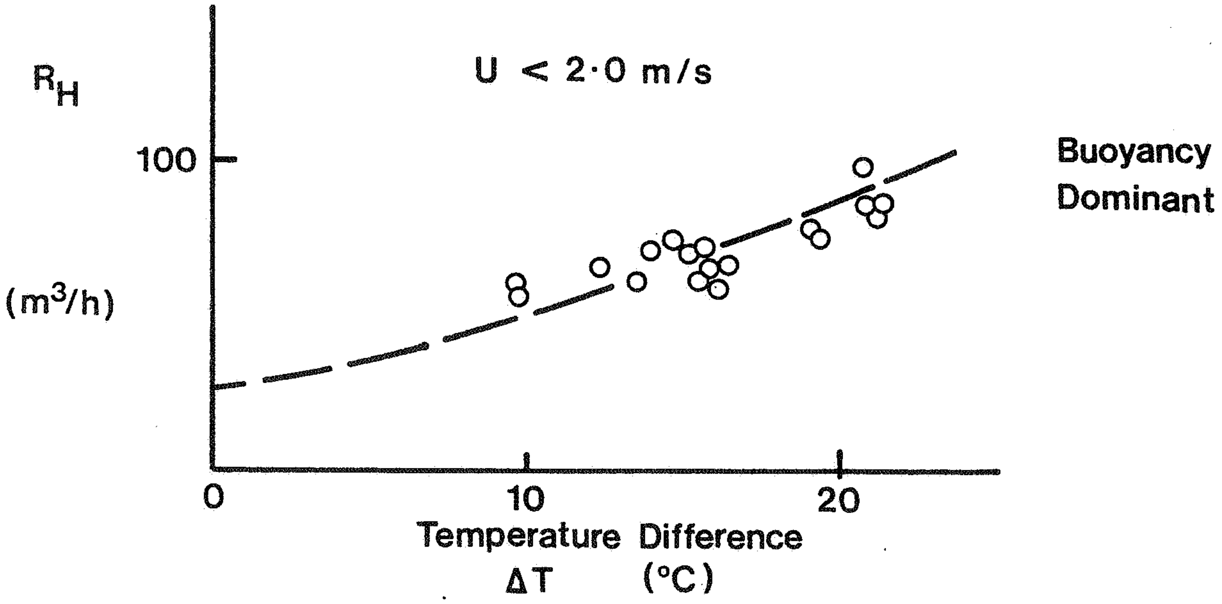
Examples of the variation of whole-house ventilation rates which arise from weather changes are shown in Figure 3 for a detached house. The two sets of results correspond to conditions when buoyancy and wind were dominant respectively. The flow rate rises from about $50m^3/h$ with a temperature difference of 9°C, to about $170m^3/h$ with a wind speed of 9 m/s. This level of variation i.e. by a factor of about three, is probably fairly typical of the effect of weather changes in the UK climate. The effect on room ventilation is more complex, as can be seen in Figure 4 which shows some of the room rates of a terraced house when the whole-house rate was nearly constant. The results in Figure 4 are plotted against wind speed to show that even when buoyancy is dominant as far as whole-house rates are concerned, the room rates can still depend on wind speed.

However to some extent, the results in Figure 4 give a pessimistic view, because they are the fresh air flow rates into the rooms. The total flow of air through the rooms (ie. the room air change rate) will be less influenced by weather.

4.3 Window-opening

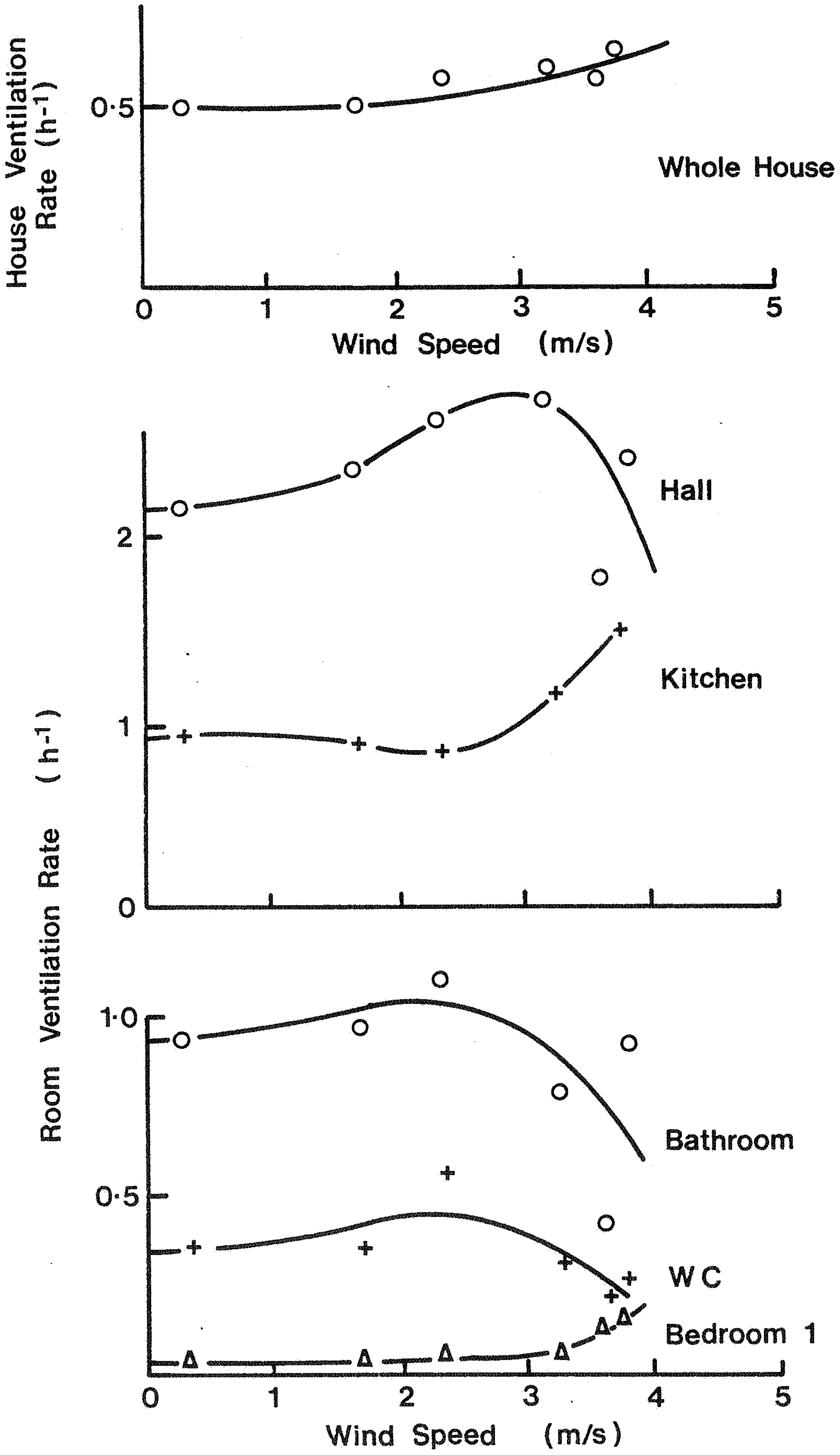
The major way (apart from an extract fan) in which occupants can exercise some control over natural ventilation is by opening and closing windows. There is evidence that open windows are fairly common in the UK(Ref.14). The reasons why they are opened and why they are closed are less well understood, but there seem to be definite associations with some weather parameters, occupancy pattern and family size (Ref.14).





MEASURED VARIATION OF HOUSE AIR CHANGE RATE R_H WITH WIND AND BUOYANCY

FIG. 3



MEASURED EFFECTS OF WIND ON WHOLE HOUSE AND ROOM VENTILATION RATES (ΔT=19°C)

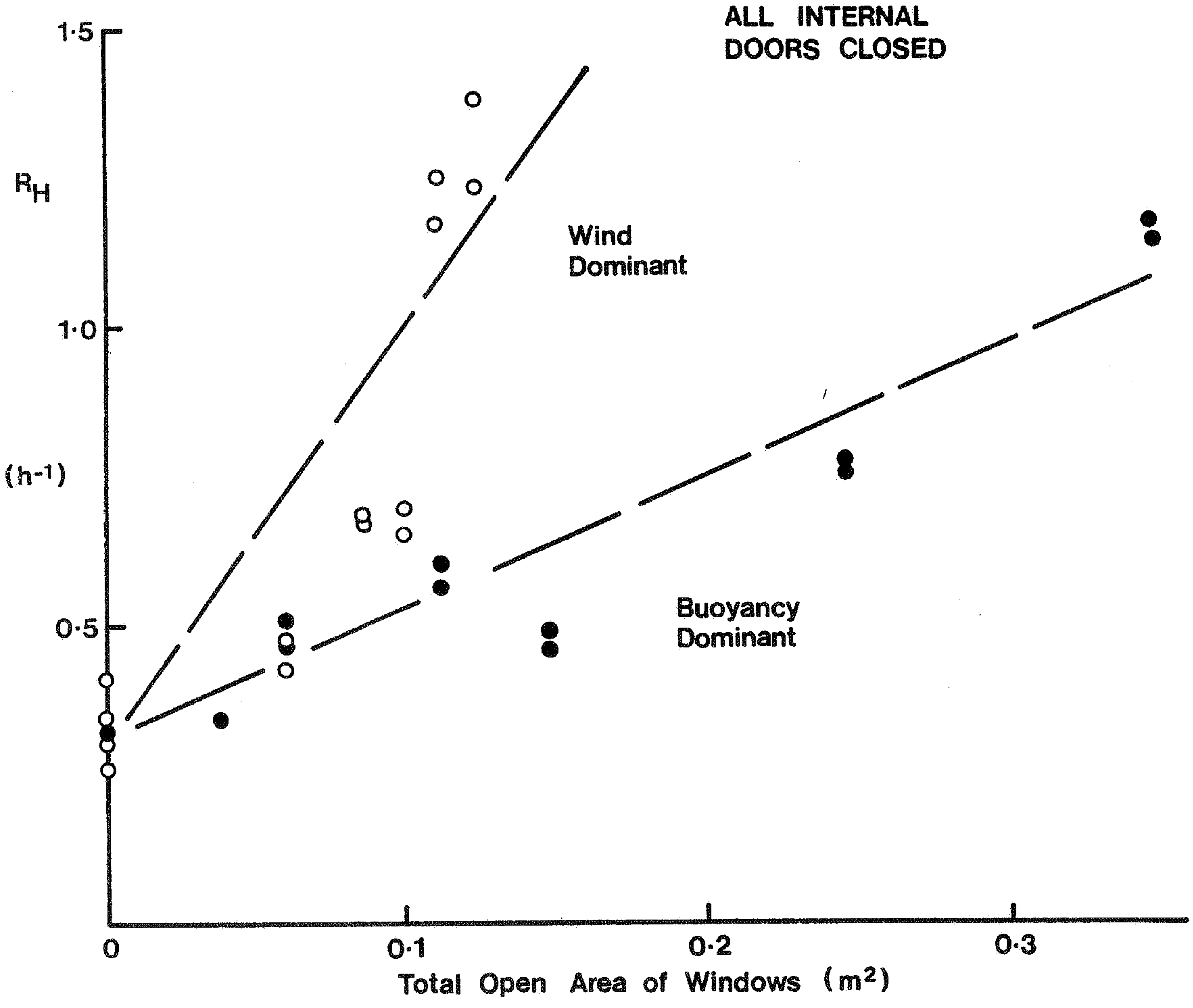
FIG. 4

The importance of window-opening to ventilation design is partly due to the very high ventilation rates which can occur. Air change rates ranging from 0.4 to 20.0 per hour are reported in Ref. 15, depending on such factors as number of open windows, their position, degree of opening and weather.

One of the criticisms of windows as a control device is that they offer only coarse control. If they are left open unnecessarily high ventilation can give rise to energy wastage. A possible way of alleviating this problem is to instal air vents which can be opened and closed, and which can be used as a fine control.

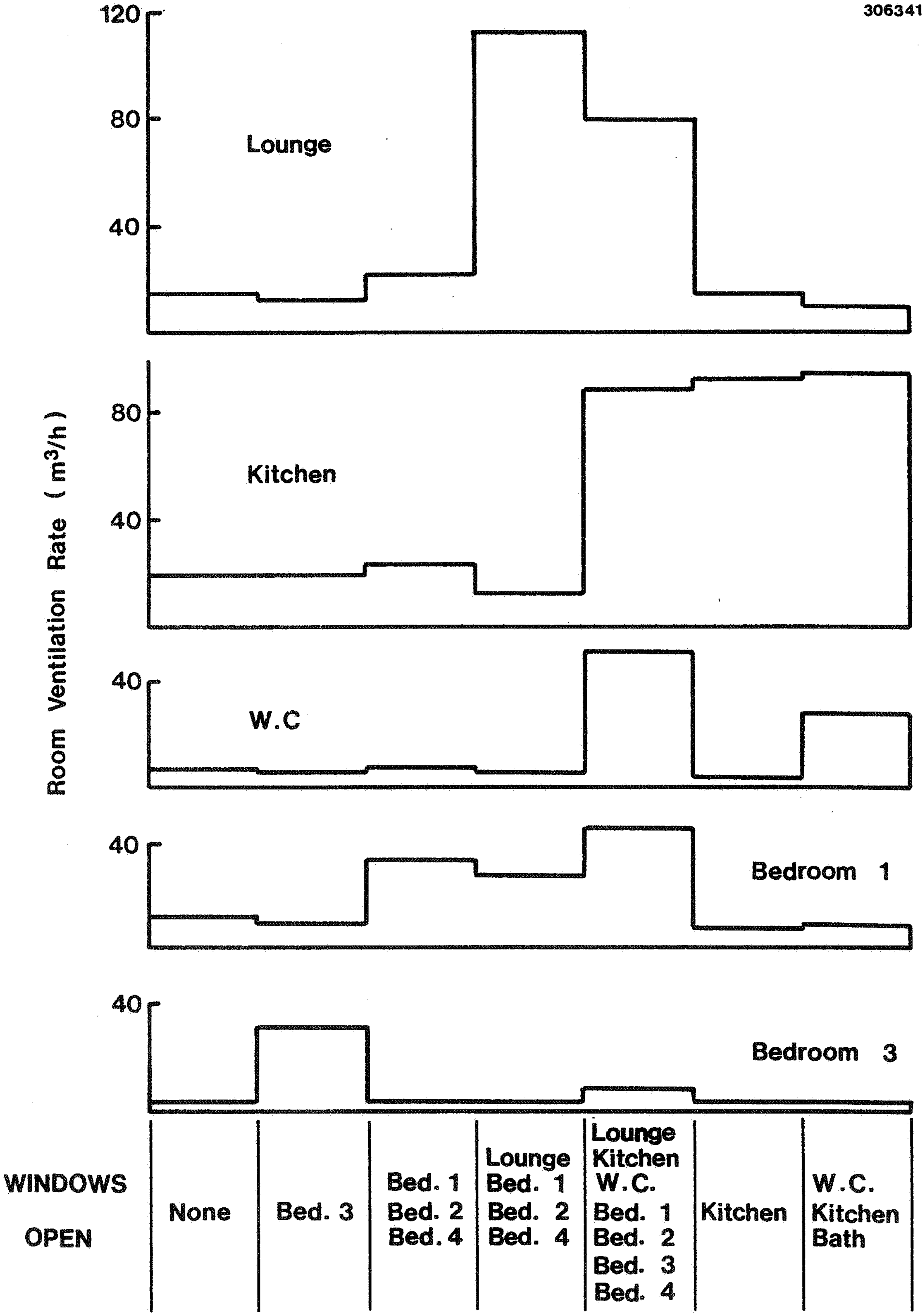
An investigation of the effects of fairly small openings has been carried out in a detached house equipped with sliding windows (they were opened to a gap of 25mm). Figure 5 shows the whole-house air change rates for a variety of window combinations and for two weather conditions where wind and buoyancy were respectively dominant. Although window-opening did cause large increases in air change rates, the values observed are at the low end of the range reported in Ref. 15. This is partly due to the small openings used in the present study. However it is probably also due to the fact that all of the internal doors were closed, whereas the data of Ref. 15 was obtained with open doors. When a room containing an open window has its internal door closed, the effect of the window will tend to be confined to the room. It will have less effect on the rest of the house when the open area of the internal door is much less than the opening in the window. Figure 6 shows some of the room ventilation rates for the buoyancy-dominant cases in Figure 5.

The measurement technique developed by British Gas can be used with doors open or closed, and Figure 7 shows some results which illustrate the effects of the doors. The tests were carried out in a terraced house with an upstairs window opened to a gap of about 75mm. For one set of results all doors were closed, and for the other two doors were opened (one being in the room with the open window). The results indicate that data obtained with



EFFECT OF WINDOW OPENING ON HOUSE AIR CHANGE RATE R_H FOR TWO WEATHER CONDITIONS

FIG. 5



EFFECT ON ROOM VENTILATION RATES OF SMALL WINDOW OPENINGS. BUOYANCY DOMINANT

FIG. 6

all doors open gives a pessimistic view of the effects of window-opening. In practice the door to the room containing the open window is equally likely to be closed. In which case the effect of the window would be to increase the air change rate of the room by a large factor, but with a relatively modest increase to the whole-house rate.

5. NATURAL VENTILATION DESIGN

As noted in Section 2, the main purpose of natural ventilation design is likely to be to maximise the term in square brackets in equation 1. This basically means that the design process should aim: -

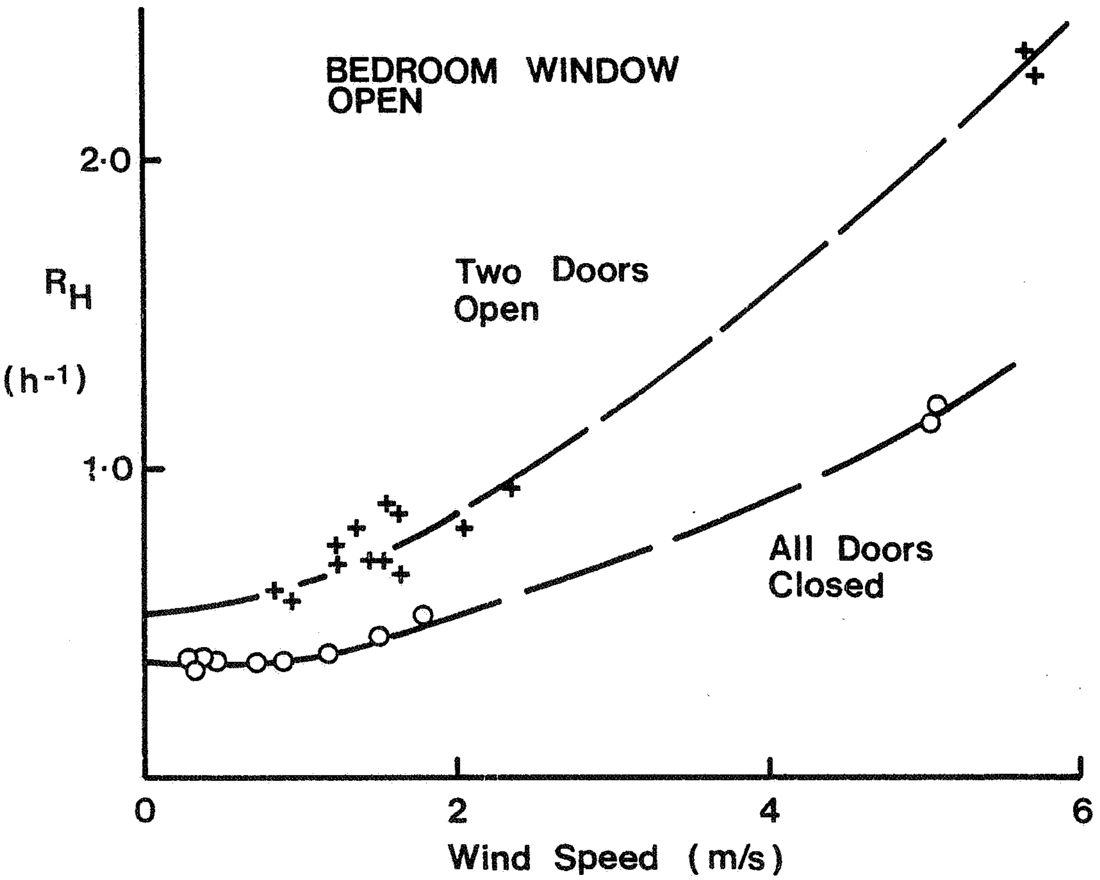
- to ensure a basic level of ventilation under specified weather and house conditions
- to minimise the variations due to weather
- improve occupant control

These three aims can be dealt with under the headings used in the previous Section.

5.1. Leakage

The achievement of a basic level of ventilation is closely connected to the achievement of a known leakage, but the discussion of leakage in Section 4.1 was basically a catalogue of problems for the designer.

In theory all of these problems can be overcome if the dwelling can be constructed such that the leakage due to component and background openings is negligible. The desired leakage and leakage distribution can then be achieved with the installation of permanent air vents. The low-pressure leakage characteristics of these can be measured in the laboratory, thus enabling ventilation to be more reliably predicted. Basically what is required is an airtight structure. Techniques for achieving this have been developed in Sweden (Ref. 16), because airtight dwellings are needed for proper operation of balanced mechanical systems.



MEASURED EFFECT OF INTERNAL DOORS ON HOUSE AIR CHANGE RATE WITH ONE WINDOW OPEN

FIG. 7

However, there are arguments against such a radical approach. It would require the adoption of new and probably more costly construction techniques, which might be difficult to justify on the grounds of theoretical improvements to ventilation and/or cost-effectiveness, particularly when it is remembered that window-opening by the occupant can substantially increase leakage. Moreover, the concept of airtight construction for dwellings may be questionable from the environmental and safety viewpoints, because air vents can be sealed (and mechanical systems can be switched off).

An alternative approach is to accept some leakage in the construction, but to ensure that it lies within certain limits. Providing it is not too large, background leakage has some desirable features i.e. it offers a base level of ventilation which it is difficult to reduce, and air which enters is generally well distributed and less likely to cause draughts. Adoption of this approach implies the adoption of a leakage standard and some means of monitoring it. Assumptions would need to be made about the characteristics of the background leakage. The level of uncertainties introduced by these assumptions would depend on the extent to which the leakage was increased by the installation of permanent vents.

Neither of the above alternatives has been adopted in the UK. However if the basic ventilation level is to be included as part of the design, one or other alternative would probably be necessary.

5.2 Weather

A possible way of reducing variations due to weather is to minimise the effects of wind. This might be done by maximising the effects of buoyancy, which would be assisted by maximising the heights between purpose-provided openings i.e. low-level vents on the ground floor, high-level vents on the upper floor. The adoption of vertical ventilation ducts, as used in some European countries, might also be considered. A more radical possibility is the use of sheltering (e.g. by trees) to reduce the pressures generated by the wind.

Another possibility, which would act on both buoyancy and wind effects, is the use of vents which in some way prevent high flow rates. Such vents are sometimes described as "constant-flow" vents. Before considering their use, however, one would need to be assured of their long-term reliability.

There are other possibilities connected with the siting of vents in relation to prevailing wind directions. Terraced houses with only two exposed surfaces obviously present a problem here, and perhaps consideration could be given to the alignment of the terrace relative to prevailing winds.

5.3. Occupant Control

One way in which occupant control might be improved is to install variable vents which offer a finer control than that normally associated with windows.

Extract fans also offer better control than windows, particularly when high ventilation rates are required. They have a fixed flow direction and they are less likely to be left operating, especially when they switch off automatically.

Both of the above options are already in use in the UK, and so it should be possible to determine their effectiveness.

A more radical option is the use of tight internal doors (perhaps self-closing) on bathroom and toilet. These rooms could then be well-ventilated with minimal spread of odours and moisture to other parts of the dwelling. This option might also be considered for other rooms, to reduce the undesirable aspects of window-opening.

6. CONCLUSIONS

Design techniques for natural ventilation should aim to (a) achieve a basic level of ventilation under specific conditions, (b) minimise variations due to weather and (c) improve the potential for occupant control. Several possibilities have been outlined in this paper which offer improvements in each of these areas.

Further research is particularly required to determine the accuracy with which (a) can be achieved, even though ventilation requirements are complex and for design purposes they are often expressed in a very simplified form.

A perfect energy-efficient system would be one which satisfied the ventilation requirements at all times. Natural ventilation systems can never achieve this ideal, because random variations occur due to weather and because occupant control is not precise. However, by paying attention to the aims (b) and (c) above, it should be possible to make significant design improvements in these areas.

Neither do current mechanical ventilation systems satisfy the above ideal. They are theoretically more energy-efficient, but in practice this theoretical potential may be undermined by the fact that such systems are not cost-effective. The argument that mechanical systems with heat recovery are cost-effective, because natural ventilation gives excessive energy consumption due to window opening, remains to be proven. The high air change rates sometimes associated with open windows may be overestimates, because internal doors are not always open.

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