# THEORETICAL AND EXPERIMENTAL STUDIES OF HEAT LOSS DUE TO VENTILATION

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## SUMMARY

Two techniques for investigating ventilation heat losses in houses are described. The first is conventional insofar as it is experimental, but it has novel features which offer several advantages over other experimental methods.

The second technique is rather unconventional, because it is based on the use of a theoretical prediction method. For such use it is necessary that the method be accurate, and evidence in support of this is presented. The use of the method for carrying out hypothetical investigations is illustrated by simulating the operation of mechanical systems in a house with different degrees of sealing. In this way the house leakage rates required for the systems to operate as designed can be found.

## 1. INTRODUCTION

The purpose of this paper is to describe two techniques for investigating ventilation which have been developed by British Gas. Consideration is given to ways of monitoring the heat loss, such as one might wish to do with a test house. An obvious way to do this is to monitor the ventilation directly with an experimental technique. Ideally this should be done continuously throughout the period of interest, but if this is not possible one could initially derive a relation between meteorological conditions and measured ventilation rates and then monitor only the meteorological conditions continuously.

The first technique described has been developed to allow the above procedure to be carried out. In this sense it might be called conventional. However it will be seen that it has several novel and important features.

The second technique is, perhaps, unconventional in that it is based on a prediction method using a mathematical model. Essentially, certain physical characteristics of the dwelling are measured at the start of the monitoring period. These measurements and the continuously monitored meteorological conditions are used as data to obtain predictions of the ventilation rates. An important feature of both techniques is that the flow rates of fresh air into individual rooms are obtained. It is often desirable to know these individual rates rather than their sum (the overall rate), because the manner in which air enters and leaves a dwelling can be as important as the magnitude of the total amount entering.

When considering ventilation heat losses there is a tendency to concentrate on the overall ventilation rate of the dwelling. The overall rate is of course of prime importance for determining the size of central heating plant and for assessing energy conservation measures, and we will concentrate on this rate in the presentation of our results. Nevertheless, for well insulated houses it becomes important to know individual room flow rates. In such houses the heat load corresponding to ventilation losses is a large proportion of the total, and problems with radiator sizing and cold draughts are likely to be encountered.

In the following sections, the experimental technique is described first and some results obtained from continuous monitoring of a house are presented. This is followed by a description of the theoretical method and a simulation of continuous monitoring (for a different house, and a longer period).

This form of presentation has been adopted to emphasise our view that the two techniques are complementary. Each has its own advantages and disadvantages, and although in the past little use has been made of theoretical methods it seems probable that with improvements in their accuracy they will be much more useful in the future.

## 2. THE EXPERIMENTAL APPROACH

### 2.1 Continuous measurement of ventilation rates

There are two basic methods for continuous measurement of ventilation rates in houses which are in current use. The first of these, repeated dosing (1), is based on a tracer decay method. A tracer gas is injected into the air of a house, mixed with it and then allowed to decay. The changing tracer concentration is monitored by discrete or continuous sampling. After a given time interval, or when the tracer concentration falls below a given level, more gas is injected and the monitoring of concentration is resumed. In this way a series of decay curves is obtained from which it is possible to estimate the average ventilation rate during the time interval between successive injections of tracer gas.

In the second method, constant concentration (2), which is the one we have adopted, the tracer gas concentration is not allowed to decay but is maintained constant. The achievement of a constant concentration is a problem in control engineering in that the air in each room of the house must be sampled regularly and the correct amount of tracer gas must be injected to hold the required target concentration. The amount of gas injected is directly proportional to the amount of tracer gas lost from the room since the previous sampling. By measuring this amount of gas we thus measure the volume of fresh air entering each room of the house.

The main advantage of the constant concentration method over the repeated dosing method is that it allows simultaneous monitoring of the rate of fresh air entering each room of the house. This would be very difficult to achieve with the repeated dosing method. It is also felt that the constant concentration method is inherently more accurate, because it is easier to maintain a uniform concentration throughout the house, particularly for the case when internal doors are closed. Another advantage is that it is relatively simple to estimate crossflow between cells (e.g. a loft) by using an additional tracer gas.

### 2.2 The automatic ventilation monitoring system

Our system consists of two networks of solenoid valves. One network of valves controls the sampling of air in each room, the other controls the injection of tracer gas to maintain the target level. The solenoid valves are activated by a command from the central computer logger which controls both the sampling and the injection sequences. The sampling lines are purged continuously to ensure that a fresh sample of room air reaches the analyser and all lines are of equal length to minimise differences in flow resistance. The rooms are sampled in sequence for 6 seconds each. At the end of that period the analyser output is read by the computer and the injection period necessary to maintain the target concentration in that room is calculated. The relevant injection valve is then opened and the next room in the sequence is sampled. When the injection period has elapsed the computer closes the valve and stores the time for which the valve was open.

Every half hour the results are summarised and the volume of air entering each room together with the relevant temperature and weather data is printed. A more detailed description of this system has been published (3) and a full one is in preparation.

### 2.3 Experimental results

One advantage of continuous ventilation monitoring over discrete measurement is that it is possible to observe subtle variations due to wind speed and direction changes more quickly, more accurately and with less effort. Figure 1 shows the whole house air change rate, R, measured for a house with all doors and windows sealed. The house is the end unit of a row which runs from East (90°) to West (270°). The ground floor is solid, the walls are cavity filled with fibreglass, the doors and windows are of standard English type and are located mostly in the North and South faces of the building with some small windows in the East face.

Figure 1 shows the whole house natural air change rate recorded in 9 successive 30-minutes periods. The doors and windows being sealed, the majority of the ventilation air entered through background leakage

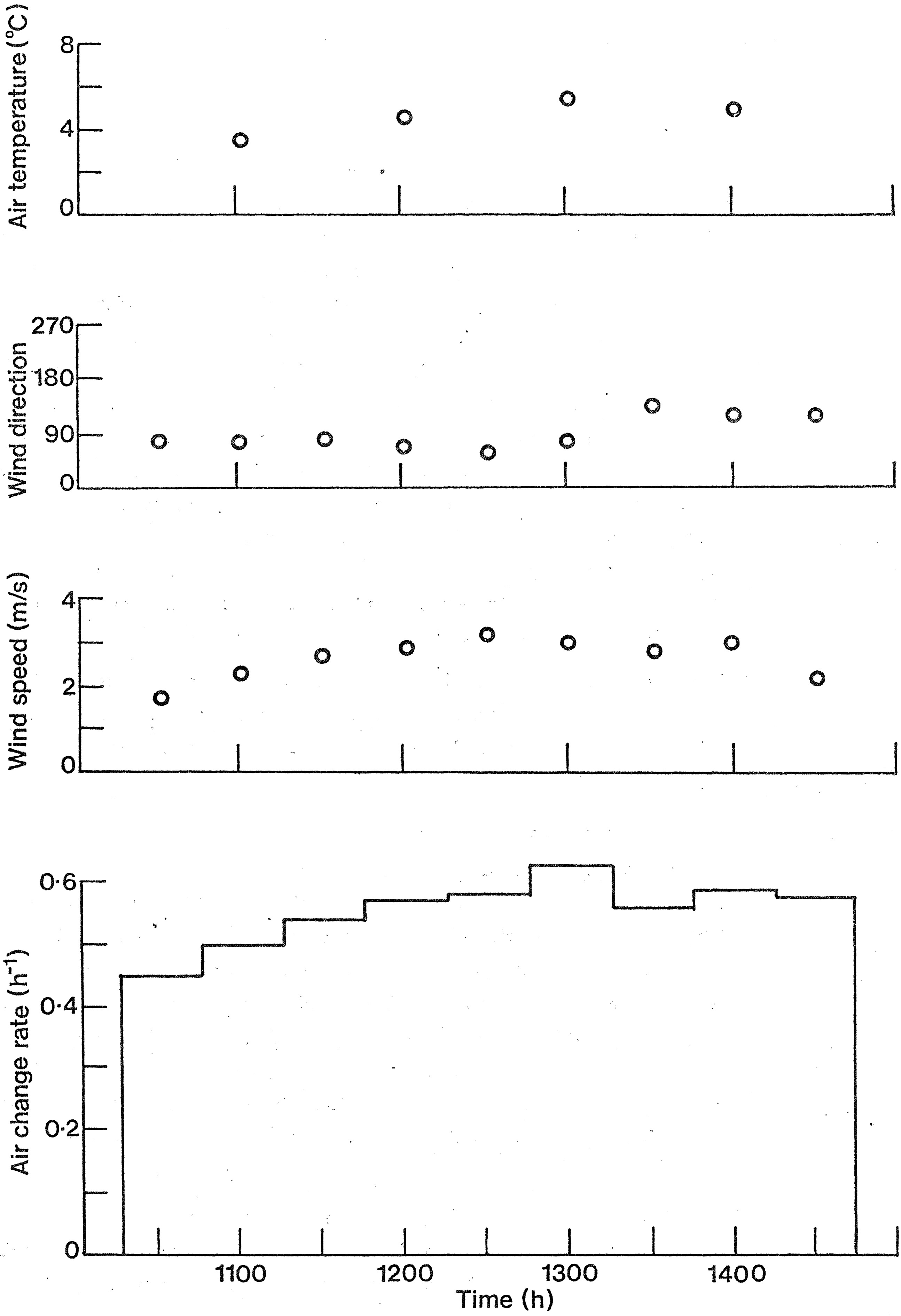

FIGURE 1 METEOROLOGICAL CONDITIONS AND MEASURED $\frac{1}{2}$ HOUR AVERAGE AIR CHANGE RATES

paths and the air grille in the kitchen. It is interesting that, despite the uncertain nature and distribution of these background leakages, the whole house air change rate correlates positively with the wind speed. There may also be correlation with the wind direction and ambient temperature but during this test they both remained roughly constant and so differences in air change rate, R, are attributable to changes in the wind speed although the total air change may be due to wind and "stack" effects.

## 3. THE THEORETICAL APPROACH

### 3.1 The prediction method

An early version of the method has been described in (4), and descriptions of the latest version will be found in (5) and (6). Hence only the main features are given here.

The basis of the method is an iterative solution of the continuity equation and the equations which describe the steady flow of air through openings in the dwelling as a function of pressure. Thus quasi-steady flow is assumed. For natural ventilation the driving pressures are generated by wind and buoyancy ("stack effect"); account of mechanical ventilation can also be included. A steady-state solution is determined by varying the relative pressures in each room or cell until the continuity and flow equations are satisfied. An approximate allowance is then made for ventilation which arises from pulsating flows through component cracks.

An important feature of the method is that it is a multi-cell method i.e. the dwelling is divided into individual rooms. Correspondingly the input data required for a solution is complex. Essentially one has to specify the pressures generated by the wind on the exterior of the dwelling and the flow characteristics of the openings in the fabric. This is a disadvantage of this method, however in time, generalised data may be built up to simplify this requirement.

The distribution of the external pressures can be obtained from scale models in an environmental wind tunnel. A small scale is necessary (we use 1/200) in order that a sufficient extent of the surroundings is modelled and such that the dimensions of the model are suitably matched to the length scales of the turbulence.

To specify the openings requires measurements to be made on the dwelling. Each opening needs to be described in terms of its position, the spaces between which it communicates and its flow equation. For purpose-provided openings (e.g. air vents) and for component cracks (cracks in doors and windows), this is relatively straightforward. The flow equations which we use have been derived from laboratory tests on three basic crack types (7). In principle, the equation for a given crack can be decided simply from its geometry and dimensions. At present however we make use of pressurisation tests, which are generally more accurate.

A similar procedure is adopted for the background leakage area of each room (this is the area of openings which remain in the room when the purpose-provided openings and component cracks are sealed). The complete specification of background areas, in particular the spaces between which they communicate, poses difficult problems and techniques for doing this will still need development. For the results presented in Figure 2 (see later) a simpler though less general procedure was used. The total background area of each room was measured and this was then distributed to the different surfaces of each room in such a way that the total area communicating with the outside agreed with that obtained from a whole house pressurisation measurement. A number of very different distributions can of course be made to fit this overall area, and so comparisons of predictions with some of the measured ventilation rates were used to select the best.

Having specified the external pressure coefficients and the flow characteristics of the house envelope, only the meteorological conditions, the internal temperatures, and any mechanical flow rates are needed for each prediction.

The accuracy of the method has been assessed by comparing predicted ventilation rates with values measured in a test house. Full descriptions of the measurements and the comparisons are given in (8) and (6) respectively. Figure 2 summarises the results of this work.

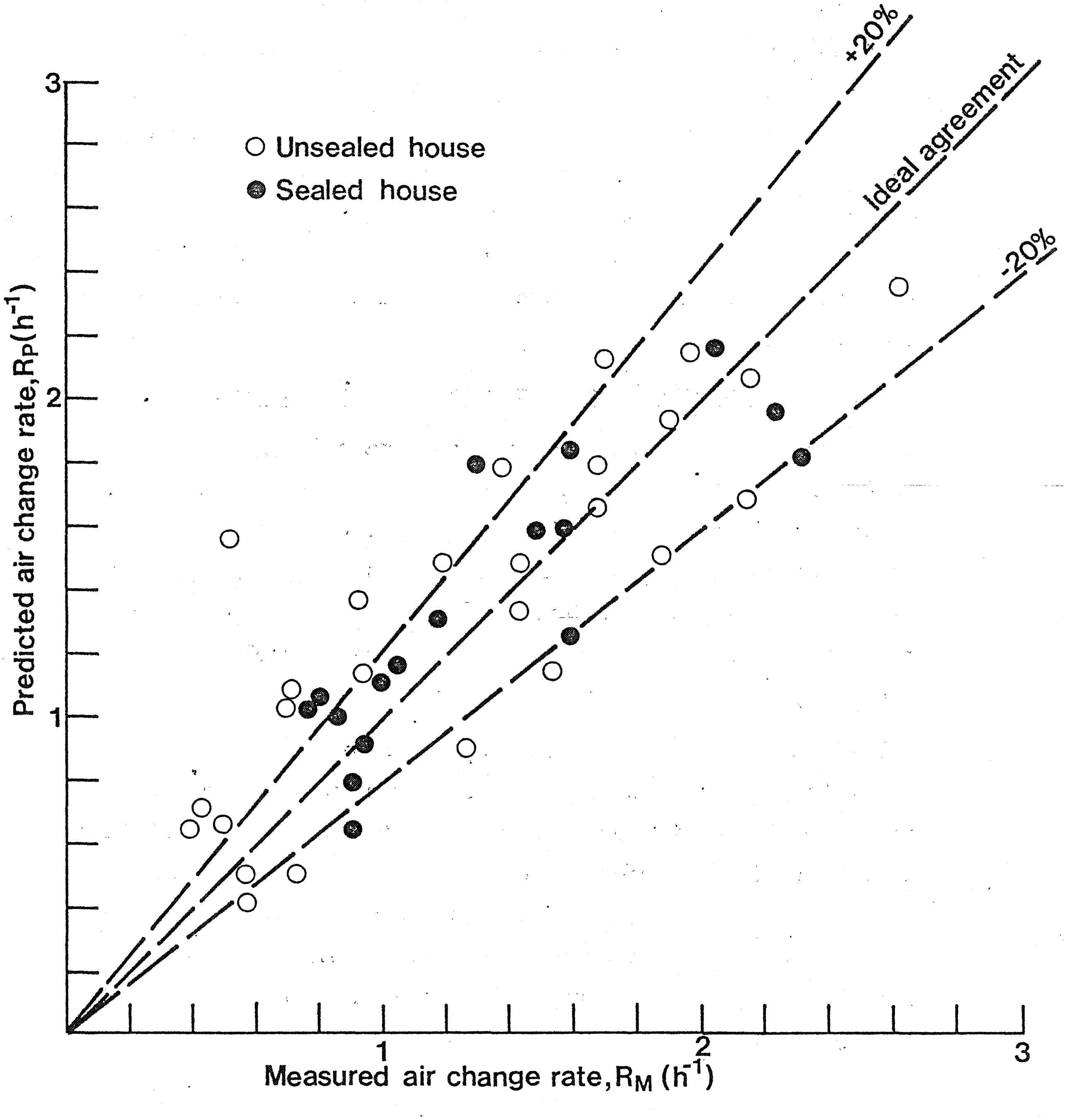

FIGURE 2 COMPARISON OF PREDICTED AND MEASURED AIR CHANGE RATES FOR MECHANICAL AND NATURAL VENTILATION, NORMAL AND SEALED HOUSE

It shows the measured values of overall ventilation rate plotted against the predicted values. The standard deviation of the ratio of predicted and measured values is 0.39 i.e. ± 20%. This is considered to be very encouraging, bearing in mind that a wide range of ventilation conditions was covered by the tests. These included natural and several mechanical ventilation systems with the house both sealed and unsealed. As mentioned above this agreement was achieved by selecting the best distribution of background areas. It should be noted however that only the natural, unsealed house measurements were used for this. It must also be noted that the method used for the measurements was not the method described in the present paper. It was in fact a less accurate tracer decay technique. Preliminary comparisons which have been made with results from the new technique indicate that the standard deviation is decreased.

### 3.2 Theoretical results - natural ventilation

The theoretical simulations have been made for a house which is situated in South London. It is a four-bedroomed detached house of 240 $m^3$ volume. It was built in 1967 and is of conventional English construction with suspended floors. It is not a well-insulated house and for the period considered here the average fabric heat loss has been roughly estimated to be 6 kW. The house is sheltered from the South and East, and exposed from the West.

Whole house air change rates and ventilation heat losses have been predicted for a winter week period, using two-hourly average meteorological data derived from Kew station records for January 23 to 29 1978 (the wind speeds have been reduced by 40% to make them more representative of the site where the house is situated, for which continuous records have not been kept). The wind speeds and directions and the ambient temperatures are shown in Figure 3. The wind direction was typically westerly, average speed was 3.5 m/s and average temperature 4.6°C.

For the purpose of illustration the simulation has been kept simple and no account of user patterns (e.g. window opening) has been taken. All internal doors have been taken as open. The calculated ventilation

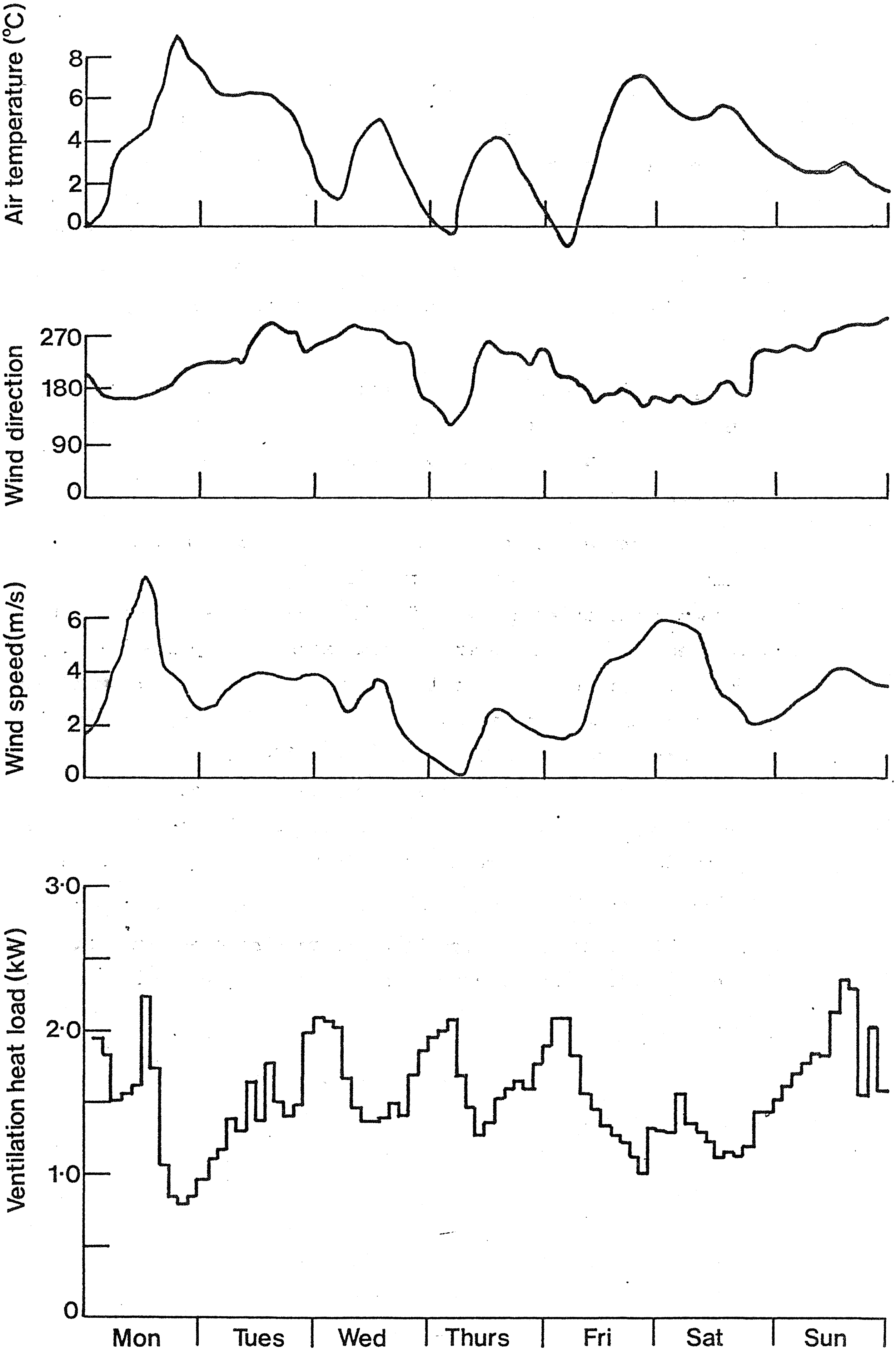

FIGURE 3 METEOROLOGICAL CONDITIONS AND PREDICTED 2 HOUR AVERAGE VENTILATION HEAT LOADS

heating load was determined simply from the heat output required to maintain a constant internal temperature of 21 °C. Only whole house values are considered here, but it is worth remembering that a lot of potentially useful information about room flow rates is obtained. An illustration of this is given in (9) where an early prediction for the living room is shown (for this simulation the wind speeds were directly taken from the Kew data, and an early version of the prediction method was used).

The predicted natural ventilation heating loads for the week are given in Figure 3. This form of presentation is similar to that used for the experimental results, so as to emphasise that the objectives of the two approaches are the same.

An important advantage of the theoretical approach is that it is a simple matter to substitute modified house characteristics for the measured characteristics. To illustrate this, simulations have been carried out with different sealing measures applied to the house. These are listed in Table 1, with their corresponding house leakage rates at an applied pressure of 50 Pa. The leakage rate can be considered as a measure of the total effective open area of the house. Our experience with the house suggests that measures (b), (d) and (e) would be very difficult to achieve in practice, and the complete sealing of windows (c) would render them unopenable, so that these are ideal conditions only.

Table 1 also shows the predicted average natural ventilation rates, and the percentage reductions relative to the normal house condition (a).

| Case | Description | Leakage at 50 Pa, in house volumes per hour $h^{-1}$ | Leakage Reduction % | Average air change rate $h^{-1}$ | Reduction % |
|---|---|---|---|---|---|
| (a) | House in actual state | 26.3 | - | 1.77 | - |
| (b) | As (a), but with both suspended floor and loft hatch completely sealed | 17.3 | 34 | 1.39 | 22.9 |
| (c) | As (a), but with all openable windows completely sealed | 18.8 | 28.5 | 1.11 | 37.3 |
| (d) | Measures (b) and (c) together | 10.1 | 61.6 | 0.51 | 71.2 |
| (e) | As (d), but half the leakage of (d) | 5.1 | 80.6 | 0.26 | 85.3 |

Table 1 The results of Sealing Measures

It can be seen from the Table that the reductions in the leakage rates achieved by floor sealing (b) and by sealing the windows (c) are similar. However the resulting reductions in ventilation rates are considerably different. In the sealed floor case the open areas affected are those which would have the stack effect as the main driving force of the flow, while in the sealed case the areas would be those expected to be primarily involved in wind effect flows. As a result, a difference in the response to sealing numerically similar effective areas is both reasonable and explicable. The extent of the difference appears to depend on the weather conditions applied.

It is also worth noting that the effect of combined floor and window sealing (d), is greater than the sum of the individual effects. This also indicates that the house needs to be treated as a complete system when determining the effectiveness of sealing measures.

The above results suggest that difficulties may be encountered when trying to produce simple prediction models, such as those depending on correlations between leakage rate and ventilation rate. For the above cases only the size and distribution of openings have been changed and yet there are significant departures from a simple relation between the two rates.

### 3.3 Theoretical results - mechanical ventilation

In addition to the simulations with natural ventilation, the house has been "equipped" with the following mechanical ventilation systems:-

| | | |
|---|---|---|
| EX5 | Extract system, mechanical air change rate | $R_M = 0.5\ h^{-1}$ |
| EX1 | " " " " " " | $R_M = 1.0\ h^{-1}$ |
| BA5 | Balanced extract and supply system | $R_M = 0.5\ h^{-1}$ |
| BA1 | " " " " " | $R_M = 1.0\ h^{-1}$ |

Generally speaking, the design aim of a mechanical system is to achieve a ventilation rate which is independent of meteorological conditions. The magnitude of the desired rate will be a compromise between minimising the heat losses and achieving a satisfactory supply of fresh air. For the above systems the desired air change rate has been taken as 0.5 or 1.0 house volumes per hour.

Figure 4 shows the minimum*, the mean, and the maximum + air change rates for the various systems (including the natural system) for the period. It is clear that as the house is progressively sealed the mechanical systems approach the design aim. The approach is more rapid for the extract system than for the balanced system, because the former pressurises the house. For the balanced system there is no such pressurisation (with internal doors open) so to reach the same level of performance more sealing is required. The extract system has reached design performance for case (d), but this corresponds to a reduction in leakage rate of over 60% and our experience suggests that the sealing measures required would not be easy to apply to the house in question.

Whether or not a system offers energy savings clearly depends on the base from which one measures the saving. If the natural ventilation heat loss for case (a) is taken as the base, then the savings are potentially the largest. However even then, significant savings do not become apparent until sealing measure (d) is adopted. If the natural ventilation heat loss for case (b) or (c), where the average natural ventilation is between 0.5 and 1.0, is taken as the base the mechanical systems look less promising from an energy saving viewpoint. For a given sealing measure the mechanical systems, not surprisingly, always give a greater heat loss than the natural ventilation. It is necessary however to remember that it is desirable that the ventilation should not fall below a minimum level, and this sets a limit on the amount of sealing that can be accepted with natural ventilation alone. However further sealing, with a mechanical system, gives the added benefit of minimising the fluctuations of the ventilation heating loads.

* exceeded 90% of the time

\+ exceeded only 10% of the time

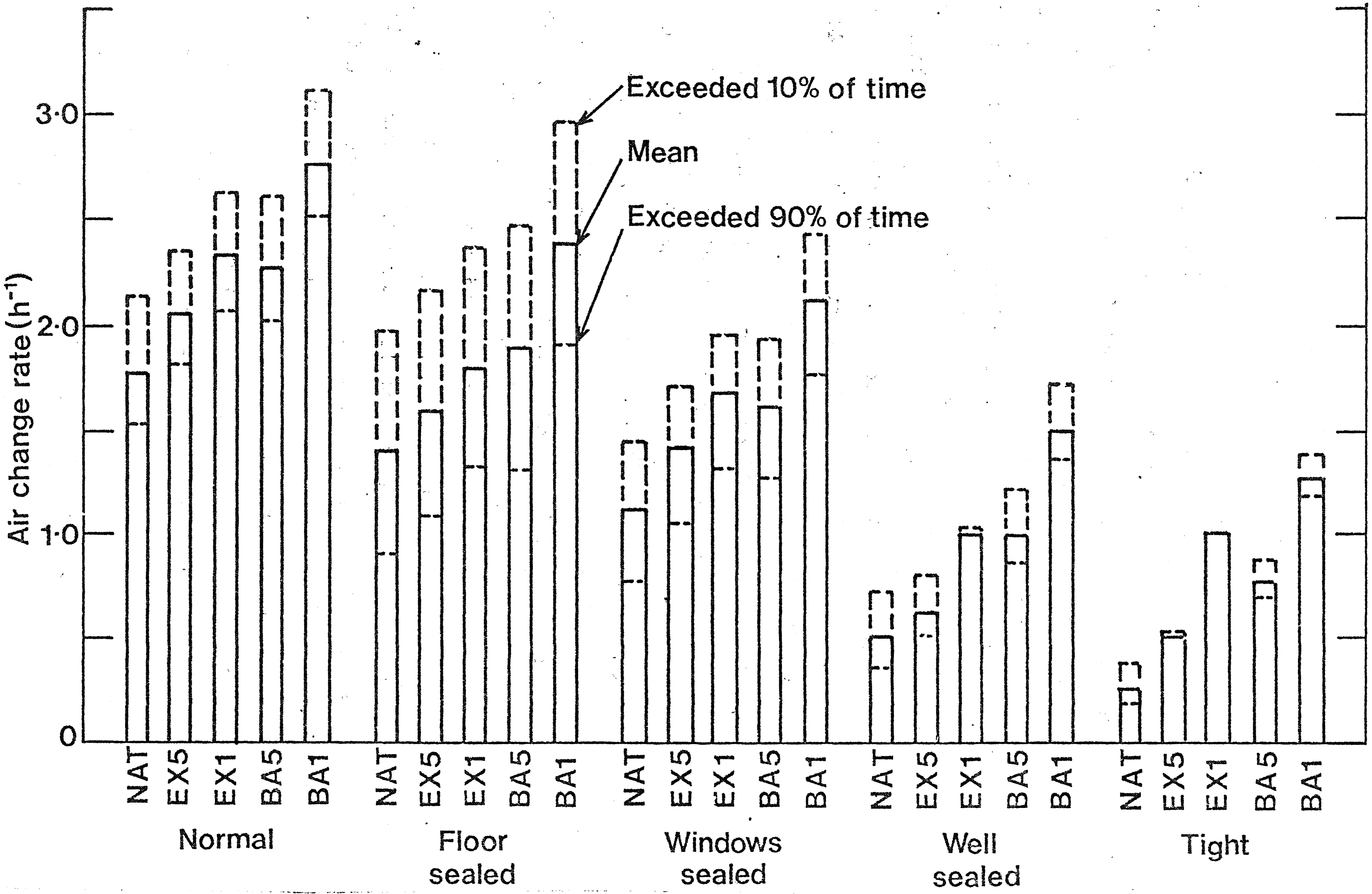

FIGURE 4 MINIMUM, AVERAGE AND MAXIMUM PREDICTED AIR CHANGE RATES FOR ALL SYSTEMS AND HOUSE CONDITIONS

The above simulations illustrate the potential of the calculation method. Consideration has not been given to the effect of heat recovery or of occupant behaviour on energy savings, which are outside the scope of this paper.

## 4. CONCLUDING REMARKS

Continuous monitoring of ventilation rates is desirable for determining heat losses encountered in practice. Two techniques for doing this have been described and illustrated with results. Both have their own particular advantages and disadvantages and are therefore considered complementary. They do however have one important feature in common i.e. they determine room flow rates rather than simply the whole house ventilation rate.

The experimental technique is at a stage where it can be used with confidence. The theoretical technique is rather unconventional and therefore needs further investigation before it can be used with equal confidence. Nevertheless results to date show that there is good reason to be optimistic about its potential.

## 5. ACKNOWLEDGEMENTS

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## REFERENCES

1. Harrje D.T., Hunt C.M., Treado and Malik N.J. Automated Instrumentation for air infiltration measurement in buildings. Princetown University (1975).

2. Honma H. VVS 7 48-53 (1972) Library translation 1940 Building Research Establishment (1975).

   Condon P.E., Grimsrud, D.T., Sharman, M.H. and Kammerud, R.C. An automated controlled flow air infiltration measurement system, University of California, Berkeley (1978)

3. Gale, R. Ventilation heat loss, outside in. Gas Engineering and Management, 19, No.11, 563-572 (1979).

4. Etheridge, D.W. and Phillips, P. The prediction of ventilation rates in houses and implications for energy conservation. CIB S17 Meeting Proceedings, Holzkirchen, September 1977.

5. Alexander, D.K. and Etheridge, D.W. Natural and mechanical ventilation rates in a detached house. Part 2: prediction. Submitted for publication in Applied Energy.

6. Alexander, D.K. and Etheridge, D.W. The British Gas multi-cell model for calculating ventilation. To be presented at ASHRAE Symposium, June 1980.

7. Etheridge, D.W. Crack flow equations and scale effect. Build. and Env., 12, 181-189, 1977.

8. Etheridge, D.W., Gale, R., Gell, M., and Martin, L.J. Natural and Mechanical ventilation rates in a detached house. Part I: measurement. Submitted for publication in Applied Energy.

9. Pickup, G.A., and Miles A.J. Energy Conservation - field studies in domestic heating. I. Gas. Eng. Communication 1086, May 1979, London.