ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING ACCEPTABLE INDOOR AIR QUALITY

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PAPER 20

# THE ROLE OF MATHEMATICAL MODELLING IN THE DESIGN OF ENERGY EFFICIENT VENTILATION SYSTEMS

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## SYNOPSIS

With the need to conserve energy, there has been a growing tendancy towards the design and construction of tight dwellings. The airtightness of older houses is also being increased in efforts to reduce energy consumption. As this process continues, it is becoming increasingly more important to pay particular attention to the ventilation needs of a dwelling.

In this paper, the various roles that mathematical models can play in the design of energy-efficient ventilation systems are explored. An example is used to illustrate how models may be used to investigate the energy implications and air distribution patterns of a range of mechanical and natural ventilation options. Particular attention is focussed on predicting the performance of these systems for a wide variety of conditions.

It is concluded that models of proven validity are an invaluable aid in ventilation design studies. They enable the performance and cost benefit of ventilation strategies to be quickly assessed and have important applications in building energy analyses.

## 1. INTRODUCTION

As a result of uncertainties in the future supply of energy, coupled with substantial increases in its cost, it has become increasingly important for many countries to focus particular attention on methods to conserve energy. In the United Kingdom, it is estimated that 51% of primary energy is used in buildings of which approximately 60% is used in the domestic sector[1,2]. This compares with the results of a recent analysis of energy statistics based on data from 15 industrialized countries in which prime energy consumption in buildings ranged from between 23% to more than 50%, with the domestic sector accounting for between 56 to 68% of this proportion[3]. Thus the conservation of energy in dwellings has become an important consideration in many national energy strategies.

Hitherto, methods to reduce energy consumption in dwellings have largely concentrated on limiting heat loss through the building fabric. It is now thought the cost effective level of thermal insulation has been attained and that future emphasis will be directed at controlling ventilation and air infiltration losses[3]. A variety of studies have shown that such losses can account for between 25% of the space heating demand in a poorly insulated dwelling to 50% for a well insulated building[4,5,6]. Hence these losses represent a substantial proportion of the domestic energy demand. However, a building cannot simply be made more airtight in an effort to reduce ventilation heat loss. An inadequate supply of fresh air and poor air distribution will result in high levels of indoor air pollution, odours and condensation. Thus proper provision for ventilation must be made if energy reductions are to be successfully achieved without detriment to the indoor environment.

In temperate climates, the normal method of ventilation has often been to rely on the natural movement of air through adventitious openings in the building fabric, supplemented by the opening of windows. On the otherhand, in countries with severe climates and limited energy resources, the need to incorporate energy efficient ventilation systems as an integral part of building services design has long been recognised. Clearly, to achieve the objective of minimising energy consumption, a general move towards the latter approach is required.

Mathematical models have an important role to play in this design process because they enable the many ventilation options to be assessed quickly and cheaply. They can also be used in cost benefit studies to identify the optimum design solution for a particular building and environment.

In this paper, some of the models which have been used in design work are reviewed and the problems associated with the use of models are discussed. An example to illustrate the role of models in determining the energy implications and airflow patterns of a range of ventilation systems is described.

## 2. MODELS IN DESIGN

One of the earliest numerical models used in the calculation of air infiltration in residential buildings is described by Gabrielsson and Porra[7]. A "multi-cell" technique was developed in which the building was divided into nodes interconnected by flow paths. The nodes represented individual rooms or regions of differing pressure and the flow paths represented the leakage between them. A series of simultaneous equations describing the flow in each path was developed and solved iteratively by determining an internal distribution such that the volume of incoming air was balanced by the outflow. The model had applications in air movement studies and proved to be a valuable tool in ventilation calculations and design work.

A similar approach was used by Jackman to analyse air movement in tall, naturally ventilated office buildings and to study various ventilation options in a two-storey dwelling[8,9]. Other models following this approach are described by Bilsborrow[10], Sander[11], de Gids[12] and Etheridge[13].

Because "multi-cell" models can be used to predict internal air movement, they are an invaluable aid to indoor air quality studies. However, they require substantial data to describe the internal flow network and often demand a significant amount of computational effort. In some instances, it is therefore advantageous to reduce the network by assuming that the interior of the building is at a single internal pressure. This generally enables the flow equations to be solved directly, thereby greatly simplifying the calculations.

This approximation is valid provided there is no significant resistance to internal air movement. The method enables overall air change rates to be determined and hence is useful in calculating ventilation heat loss. Methods based on this approach are described by Larsen[14], Nylund[15], Cole[16] and Handa[17].

A recent advance on the "single-cell" technique is described by Sherman and Grimsrud[18] and Warren and Webb[19]. In this development, air infiltration is correlated with the results of building pressurization test data, by linking the leakage characteristics of the flow paths to the pressurization results.

With the majority of models, it is possible to determine the effects on ventilation of purpose provided openings, chimneys and mechanical ventilation systems. Thus a wide range of models are available to assist in all aspects of ventilation design.

## 3. MODEL VALIDATION

A problem with many air infiltration models is that, because the availability of air infiltration data is limited, the scale of validation has been restricted. Hence the reliability of models in design applications is uncertain. One of the tasks of the Air Infiltration Centre has been to prepare reliable datasets from experimental data covering as wide a range of building design and climatic conditions as possible. This is being used to determine the full rage of applicability of models and to identify the key parameters which must be defined for reliable estimates of air infiltration. The outcome of this study will be published shortly but present results are encouraging and show that good estimates of air infiltration are possible, provided that leakage and pressure data are accurately specified.

## 4. KEY PARAMETERS

### 4.1 Leakage Characteristics

The flow through an opening is generally approximated by an exponential equation of the form

$$Q = k(\Delta P)^n \qquad 1$$

where k and n are constants describing the leakage characteristics of the opening and $\Delta P$ is the pressure difference acting across the component.

In existing dwellings, the determination of air leakage characteristics are fairly straightforward and basic data may be obtained by performing a building pressurization test. However, with a projected building such an exercise is not possible. For models to be successful in this application, it is necessary to specify the fabric or background leakage characteristics of the building at the design stage and to select the appropriate building technique. High quality control during building construction is also essential.

## 4.2 Pressure Data

The pressure acting on the building is maintained by the action of wind and stack effect. Relative to the static pressure of the free wind, the pressure resulting from wind impinging on the surface of the building is given by

$$P_w = \frac{\rho}{2} C_p v^2 \qquad 2$$

where $\rho$ = air density

$C_p$ = pressure coefficient

$v^2$ = wind speed and building height

The pressure coefficient is related to the pattern of flow around the building and is the key parameter to be defined in determining wind pressure. Coefficients based on the results of wind tunnel tests performed on simple building shapes are widely available but may not be applicable to buildings shielded by local obstructions. Much work is still required to develop simple rules to cope with this problem and in the meantime it may be necessary to perform wind tunnel tests on scale models of the building in situ.

The stack effect is described by the equation

$$P_s = 3462\ (h-n)\left(\frac{1}{Text} - \frac{1}{Tint}\right) \qquad 3$$

where h = level of opening
n = level of neutral plane
Text = external air temperature
Tint = internal temperature

In practice, the level of the neutral plane is rarely known and stack pressure is normally expressed relative to the lowest opening. This calculation should present few problems.

## 5. EXAMPLE

To illustrate the role of models in ventilation design, an example is described below. In a previous study[9], a similar model was used to assess the energy implications of providing adequate natural ventilation in a dwelling, at a design internal/external temperature difference of 4°C and calm wind conditions. The effects on energy consumption of airtightness measures and alternative natural and mechanical ventilation systems were also investigated. In the present example, an existing building is taken as the starting point.

## 5.1 Description of Dwelling

The floor plan and principal flow network of the dwelling is illustrated in Figure 1. It is a two storey, end terrace house of brick and block cavity wall construction, situated in relatively unobstructed countryside. The occupied volume of this building is approximately $227m^3$. The windows are single glazed and weatherstripped. Good mixing of air between individual rooms was assumed, equivalent to the internal doors being open.

Measurements over a range of pressures have been made to determine the leakage characteristics of the dwelling and of individual components (Figure 2). These results show that the leakage is dominated by unspecified "background" losses, which account for 71% of the total at a pressure difference of 10 Pa reducing to 65% at 50 Pa. The effectiveness of weatherstripping is also clearly illustrated, with the total window leakage being lower than that through either of the doors. By UK standards, the house is particularly airtight and has an air change rate of approximately 9.8 $h^{-1}$ at a pressure difference of 50 Pa. This compares with a mean value for 19 modern dwellings tested by the Building Research Establishment, of 13.9 ach[20]. The tightness of the building has been confirmed by a number of air infiltration tracer gas measurements which range in value from between 0.21 and 0.51 ach.

The model was used to investigate the variation in hourly air infiltration rate throughout a heating season for the building situated in its present location and for two other classes of terrain. The mean infiltration rate, energy consumption and pattern of air flow was also determined. The model was then used to study the effects on energy consumption and air change rate of alternative ventilation systems and airtightness measures.

## 5.2 Input Data

The flow parameters used in the model were based on the results of the component and building pressurization tests given in Figure 2. The component leakage characteristics were applied directly and the remaining background leakage was distributed uniformly about the envelope of the building. It was assumed that the background leakage resulted from cracks in joints in the inner leaf of the construction and were therefore shielded from the direct action of wind by the outer wall. Hence only air flow through component cracks was assumed to be influenced by wind pressure.

The climatic data is given in Table 1 and is based on statistical relationships between hourly mean wind and temperature throughout the heating season. The data was obtained from the Meteorological Office and is available for several localities in the UK. The wind data refers to the "meteorological" wind speed measured at a level of 10m above the surface in open country and may be corrected to give the wind speed for other terrains and levels by using the equation

$$\frac{U}{U_{10}} = Kz^a \qquad 4$$

where $U$ = wind speed at desired level (building height)

$U_{10}$ = meteorological wind speed

$z$ = building height

and $K$ and $a$ = constants dependent on terrain[21]

## 5.3 Calculation Method

By using each combination of wind and temperature as input data to the model, it is possible to determine the air infiltration rate for each set of conditions. An alternative method is to calculate infiltration for a representative range of data and to construct a set of infiltration curves as illustrated in Figure 3. The infiltration for any set of climatic data can then simply be determined from the graph. Provided that the wind pressure on the building is not significantly influenced by local obstructions, these infiltration curves will be valid for any climate or terrain. Thus the designer is quickly able to visualise the relative importance of the various parameters influencing air infiltration.

It can be seen from Figure 3 that, in this example, there is some dependancy on wind direction, with a reduction in infiltration rate of approximately 40% for wind along the length of the building. This reduction was verified by measurement and it was estimated to apply to variations in wind direction of no more than $\pm 10^{\circ}$. Thus, for the purposes of energy calculations and general design studies, the higher rates of infiltration were assumed. However, each design must be considered on its merits and, if necessary, statistical data relating wind direction with wind speed and air temperature should be used.

## 5.4 Verification

Because air infiltration measurements were available, it was possible to confirm the performance of the model and the validity of the various assumptions. On-site wind and temperature data were used in conjunction with the infiltration curves in Figure 3, to provide estimates of air infiltration. These are compared with measured values for the corresponding period in Figure 4.

Allowing for possible errors in measurement, the agreement was very good with the predicted and observed values being at least within 25% of each other and in more than half the instances within 10%. This result therefore gave some confidence in the remaining analysis.

Unfortunately, in the majority of design applications, air infiltration data will be unavailable and therefore the need for model validation is reinforced. Only by validating the model against as much test data as possible, will it be possible to rely on the model in design.

## 6. RESULTS

### 6.1 Variation in air infiltration rates

The variation in infiltration rates was determined by multiplying the infiltration for each combination of wind and temperature by the duration of occurrence. The results are illustrated in Figure 5 for three classes of terrain. These are

- countryside with scattered wind breaks
- urban
- city

As the terrain provides more shelter, the effect of wind on air infiltration reduces and there is a corresponding reduction in air change rate.

This type of analysis allows the designer to consider the tightness of a dwelling in relation to its environment and is therefore particularly important if designing for natural ventilation. This analysis also shows why it is not possible to correlate the results of building pressurization test data with infiltration, unless there is some knowledge of climate and location.

The existing dwelling is situated away from urban and city environments and, from the results given in Figure 5, has a mean air infiltration rate of 0.52 ach. This is very close to the value of 0.5 ach which is often regarded as a minimum desirable rate of ventilation. For the other terrains, the average air change rate actually falls below this figure. Depending on the weather conditions, the hourly air change rate varies between 0.15 and 1.45 and only exceeds 0.5 ach on 34% of occasions. The problem is therefore one of ensuring an adequate supply and distribution of fresh air at all times, without incurring an energy penalty. This is a problem which is taking on increasing importance as designers strive for energy-efficient buildings.

## 6.2 Ventilation Strategies

Details of air change rates and estimates of the energy required to maintain an internal temperature of 19°C against the effects of ventilation losses are summarised for the various strategies in Table 2 and Figure 7.

### 6.2.1 Existing System

The wide variation in infiltration rate of the existing system has already been described. This results in a combination of periods of unacceptably low ventilation and poor air quality, with others of high ventilation and excessive energy wastage. Another problem is the movement of air within the dwelling. The preferred flow pattern is for fresh air to enter the bedrooms and living areas and for stale air to leave via the kitchen and bathroom, where most of the moisture is generated. In this way, problems associated with high levels of internal humidity are minimised.

The model was used to analyse airflow patterns and these results are summarised in Figure 6. Figures 6a - c show that, for wind dominated infiltration, there is little prospect of achieving a consistent airflow pattern, as air movement is dependent on wind direction. The greatest potential for achieving satisfactory air distribution by natural means is by exploiting the stack effect. This is illustrated in Figure 6d for a temperature difference of 20°C and wind speed of $2ms^{-1}$. Air movement in both sides of the house is separated and therefore moist air from the kitchen and bathroom is kept apart from the rest of the building. The difficulty is to maintain the dominance of stack action against that of wind. In Figures 6e and f, it is shown that wind begins to take over from stack effect at $5ms^{-1}$, and at $10ms^{-1}$ the temperature effect is negligible.

The estimated annual energy demand to satisfy ventilation heat loss is 10.3 GJ and this was taken as a target value for the alternative ventilation strategies.

### 6.2.2 Mechanical Exhaust

The performance of two exhaust systems were analysed. The first system represented a purpose provided unit with a 0.5 ach capacity. The second represented the use of extractor fans located in the kitchen and bathroom, having a combined capacity of 0.2 ach. The assumption was made that these systems had no effect on the overall airtightness of the dwelling.

The predicted annual energy demand for the first system was found to be 14.8 GJ, thus representing an increase of 44% in energy consumption over the existing system. The mean air change rate was 0.75 $h^{-1}$ and varied according to weather conditions between 0.5 and 1.64 ach. The air flow patterns are illustrated in Figures 6g to i, and show that air movement is dominated by the exhaust system throughout the wind range. Apart from the ventilation system itself, the remaining outflow is into the roof space. Hence the system can be used to provide a satisfactory direction of airflow but an energy penalty is incurred.

Approximately two thirds of the outflow is through the exhaust system and therefore there is potential for heat recovery. Such a technique would need to be exploited for this system to be viable in this particular dwelling.

The individual extractor system was found to provide some measure of control over air flow with winds up to $5ms^{-1}$ (see Figures 6j to 1). The minimum air change rate was found to be 0.3 $h^{-1}$ and an air change rate of 0.5 was exceeded for 67% of the time. The estimated annual energy consumption was 12.1 GJ but may be reduced by intermittent use of the fans. Therefore, this system could provide a satisfactory alternative without a substantial increase in energy consumption.

### 6.2.3 Existing Dwellings with 0.5 ach Balanced Ventilation

The theory describing the influence of mechanical ventilation systems on overall air change rates is explained with the aid of hydraulic models by Nylund[22]. This shows that for balanced systems the air change rate is the sum of the natural infiltration and the capacity of the system. When applied to this dwelling, the mean air change rate is effectively doubled from 0.52 to 1.02 $h^{-1}$. The air flow pattern can be adjusted to suit requirements but energy demand rises to 20.5 GJ. Fortunately, efficient air-to-air heat recovery systems are available with these systems and therefore this energy demand can be reduced. For a 50% efficiency in heat recovery, the energy demand reduces to 15.4 GJ and for a 70% efficiency it is 13.4 GJ. To match the performance of the exhaust system an efficiency of 57% is required (see Figure 7).

### 6.2.4 Building "Retrofit" plus Mechanical Ventilation

The mechanical systems described above provide adequate ventilation but do not meet the target energy demand of 10.3 GJ. To achieve this, building "retrofit" is required. The assumption was made that the leakage of the dwelling could be reduced to just below a third of its current level to conform to current Swedish airtightness regulations for single family dwellings of 3 ach at 50 Pa. Such a retrofit would necessitate considerable attention being given to background leakage but may be possible using the "House Doctor" approach[23]. The energy calculations were repeated and show that for the 0.5 ach exhaust system the demand is 11.5 GJ and for the balanced system it is 15.6 GJ. With air-to-air heat recovery, the energy demand reduces to 10.5 GJ at 50 % efficiency and 8.5 GJ at 70% efficiency. Thus energy demand has been reduced to below the target figure. Adventitious ventilation and the use of extractor fans provide insufficient air change rates in the "retrofitted" dwelling.

Having used the model to assess the performance of each system, it is necessary to select a cost effective method of achieving adequate ventilation. The results of the model provide sufficient information for this exercise and therefore the model has fulfilled a role in both design and cost benefit analysis.

## 7. DISCUSSION AND CONCLUSIONS

The example has been used to demonstrate the wide range of applications that models have in the design and analysis of ventilation strategies. They enable the performance of systems to be assessed quickly and cheaply and may be readily used in the design of energy-efficient methods to suit individual requirements.

A wide range of models of varying degrees of complexity are available to meet all design needs. These range in complexity from "single-cell" approaches suitable for the estimation of overall infiltration heat loss, to "multi-cell" methods with applications in air movement and indoor air quality studies.

Model validation is particularly important because this enables the full range of applicability of models to be determined. Work in this area is progressing well and current results are very encouraging. The Air Infiltration Centre anticipate reporting further progress on this work at a later date.

The key parameters which must be specified for accurate results have also been identified. Problems associated with determining the leakage characteristics of flow paths and the pressures acting across openings are beginning to be overcome and this is further assisting in the developing role of mathematical models in design.

As the demand for energy efficiency in buildings increases, so will the need for reliable mathematical models in ventilation design continue to grow. Only by good ventilation design, which fully satisfies the needs of the building's occupants, will it be possible to realise the additional potential energy savings in buildings.

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TABLE 1 Frequency distribution of hourly mean wind and temperature data

| Temperature range °C | Wind speed range ($ms^{-1}$ at 10m) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.0 | 0.5 to 1.5 | 2.0 to 3.1 | 3.6 to 5.1 | 5.7 to 8.2 | 8.4 to 10.8 | 11.3 to 13.9 |
| - 7.9 to - 6.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| - 5.9 to - 4.0 | 0.2 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| - 3.9 to - 2.0 | 0.4 | 0.5 | 0.3 | 0.3 | 0.1 | 0.0 | 0.0 |
| - 1.9 to 0.0 | 0.7 | 0.9 | 1.0 | 1.1 | 0.5 | 0.1 | 0.0 |
| 0.1 to 2.0 | 0.8 | 1.5 | 2.0 | 2.6 | 1.6 | 0.2 | 0.0 |
| 2.1 to 4.0 | 0.7 | 1.6 | 2.3 | 3.6 | 2.5 | 0.5 | 0.1 |
| 4.1 to 6.0 | 0.7 | 1.5 | 2.6 | 4.9 | 3.6 | 0.7 | 0.3 |
| 6.1 to 8.0 | 0.6 | 1.5 | 2.6 | 5.3 | 4.8 | 1.1 | 0.4 |
| 8.1 to 10.0 | 0.4 | 1.2 | 2.3 | 4.7 | 4.7 | 1.3 | 0.3 |
| 10.1 to 12.0 | 0.3 | 1.0 | 1.9 | 3.5 | 3.4 | 1.1 | 0.3 |
| 12.1 to 14.0 | 0.1 | 0.6 | 1.4 | 2.4 | 2.1 | 0.6 | 0.2 |
| 14.1 to 16.0 | 0.1 | 0.3 | 0.8 | 1.7 | 1.3 | 0.3 | 0.1 |

TABLE 2 Summary of results

| Ventilation option | Mean air change rate ($h^{-1}$) | Minimum air change rate ($h^{-1}$) | Maximum air change rate ($h^{-1}$) | Energy demand GJ | % time ⩾.3 ach | % time >.5 ach |
|---|---|---|---|---|---|---|
| 1. Existing dwelling with natural "adventitious" ventilation | 0.52 | 0.15 | 1.45 | 10.3 | 86 | 34 |
| 2. Existing dwelling with exhaust mech. ventilation | | | | | | |
| (i) 0.5 ach | 0.75 | 0.5 | 1.64 | 14.8 | 100 | 100 |
| (ii) 0.2 ach | 0.62 | 0.3 | 1.50 | 12.1 | 100 | 67 |
| 3. Existing dwelling with balanced mech. ventilation (0.5 ach) | | | | | | |
| (i) without heat recovery | 1.02 | 0.65 | 1.95 | 20.5 | 100 | 100 |
| (ii) with 50% heat recovery | | | | 15.4 | | |
| (iii) with 70% heat recovery | | | | 13.4 | | |
| *4. Dwelling retro-fitted to Swedish airtightness standards (3 ach at 50 Pa) | | | | | | |
| (i) .5ach exhaust | 0.56 | 0.50 | 1.08 | 11.5 | 100 | 100 |
| (ii) .5ach balanced | | | | | | |
| without heat recovery | 0.83 | 0.55 | 1.46 | 15.6 | 100 | 100 |
| 50% heat recovery | | | | 10.5 | | |
| 70% heat recovery | | | | 8.5 | | |

* *see also Reference*[9]

FIGURE 1 Floor plan of dwelling and principal flow paths

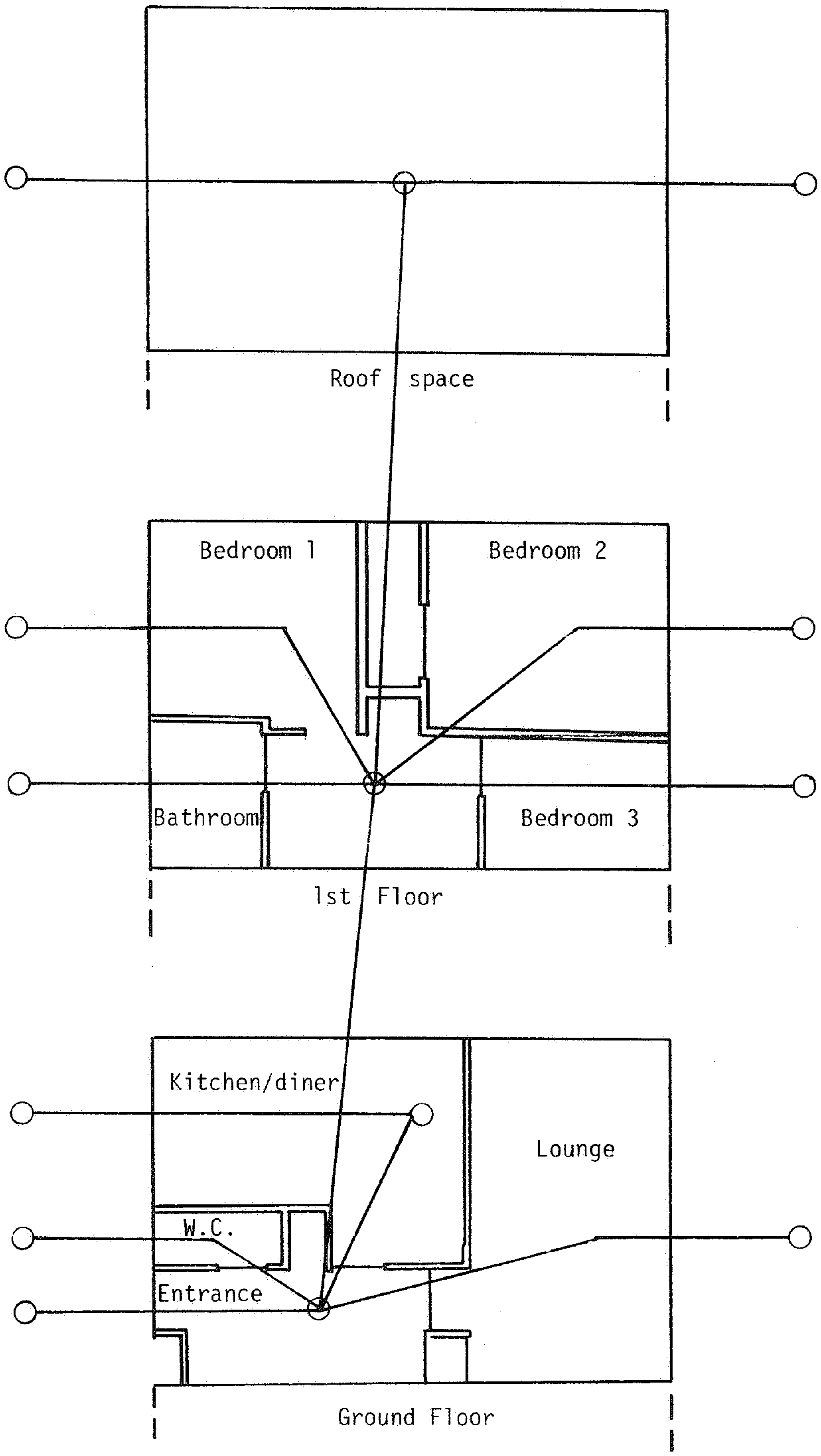


FIGURE 2 Air leakage characteristics of dwelling

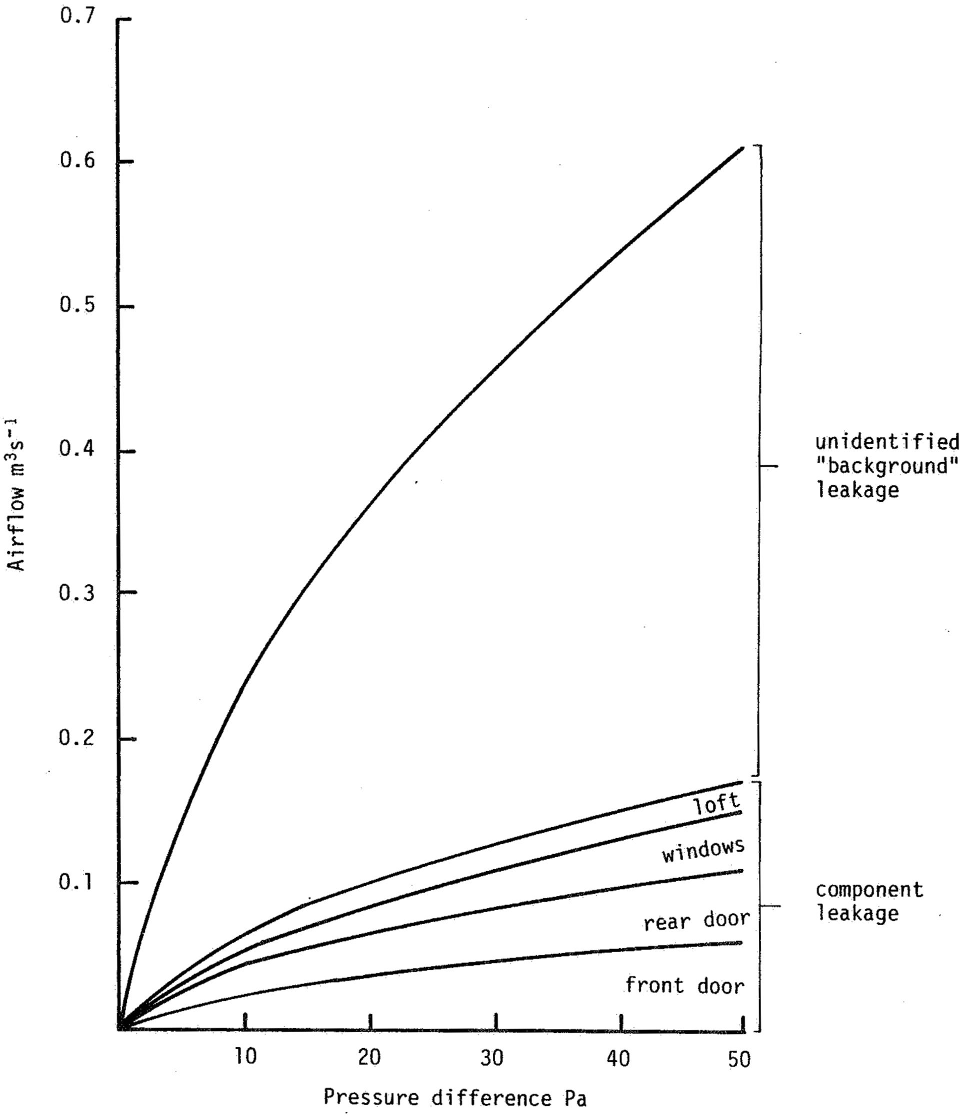


FIGURE 3 Air infiltration characteristics of dwelling

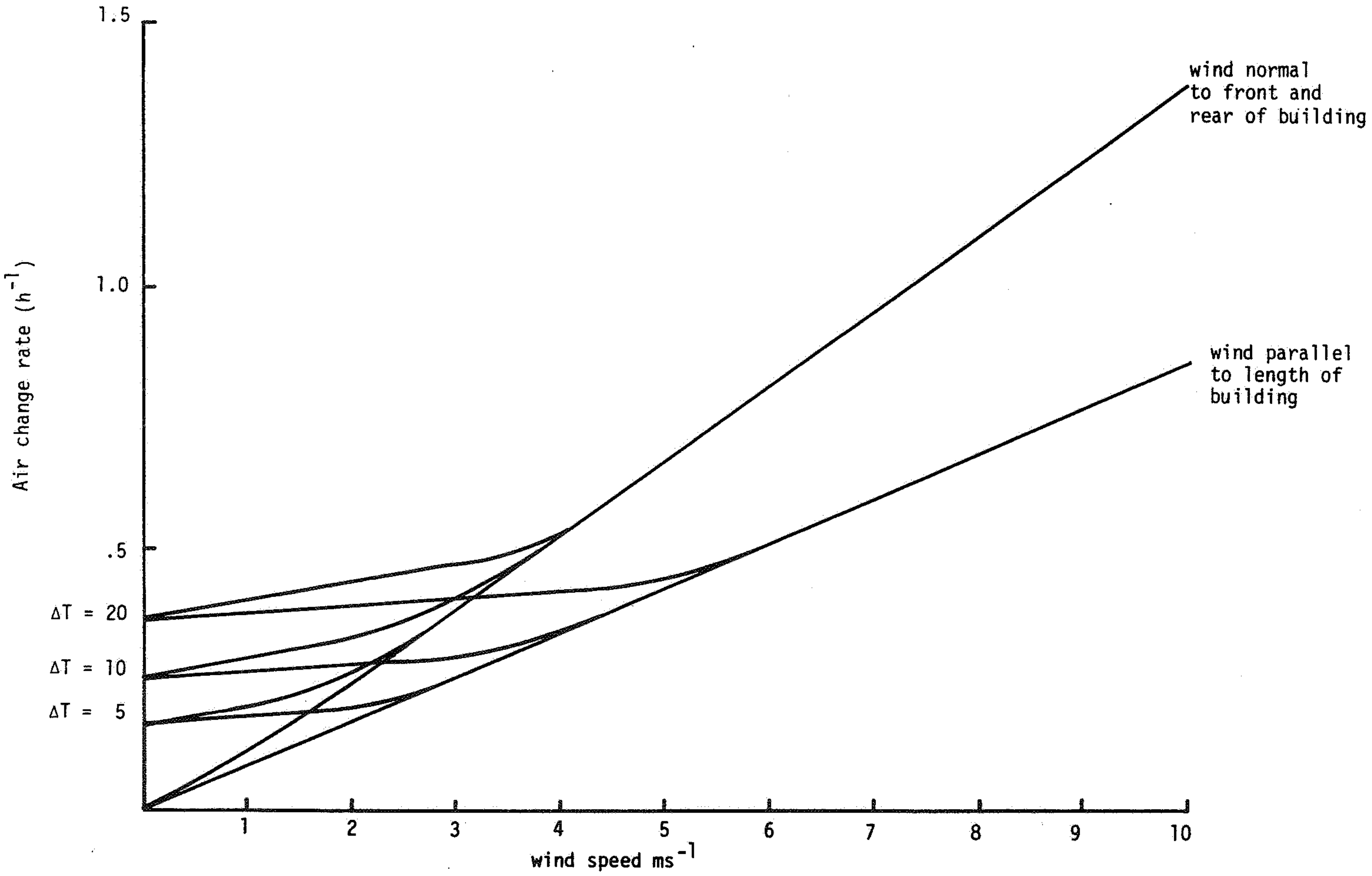


FIGURE 4 Model validation using measured infiltration data

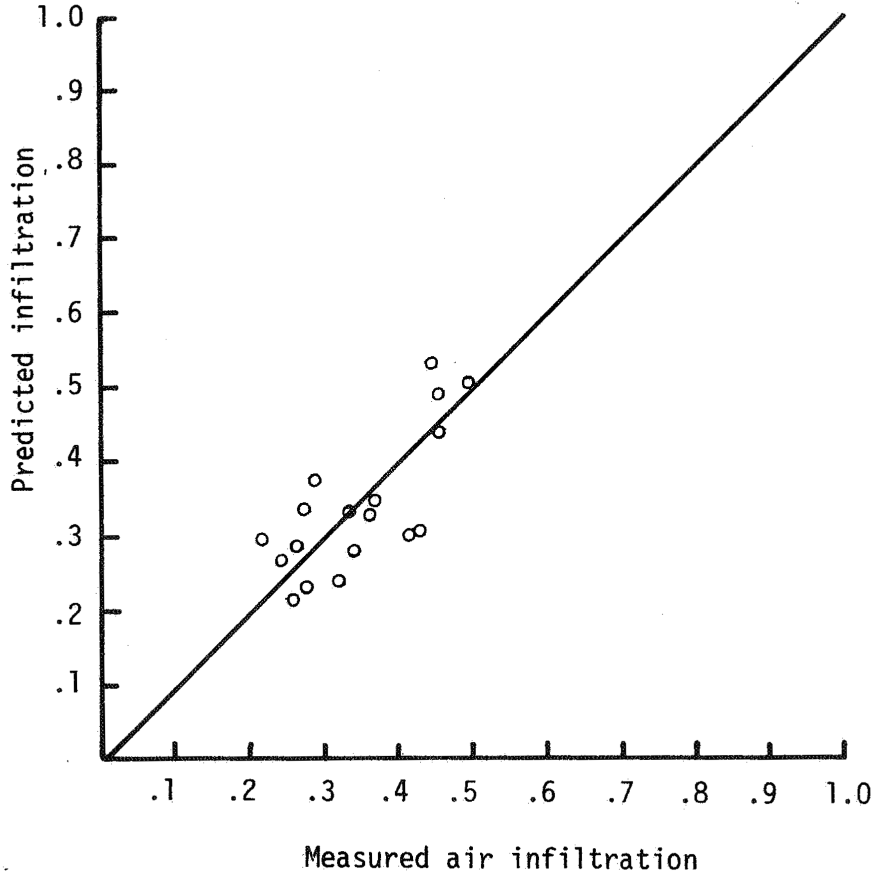
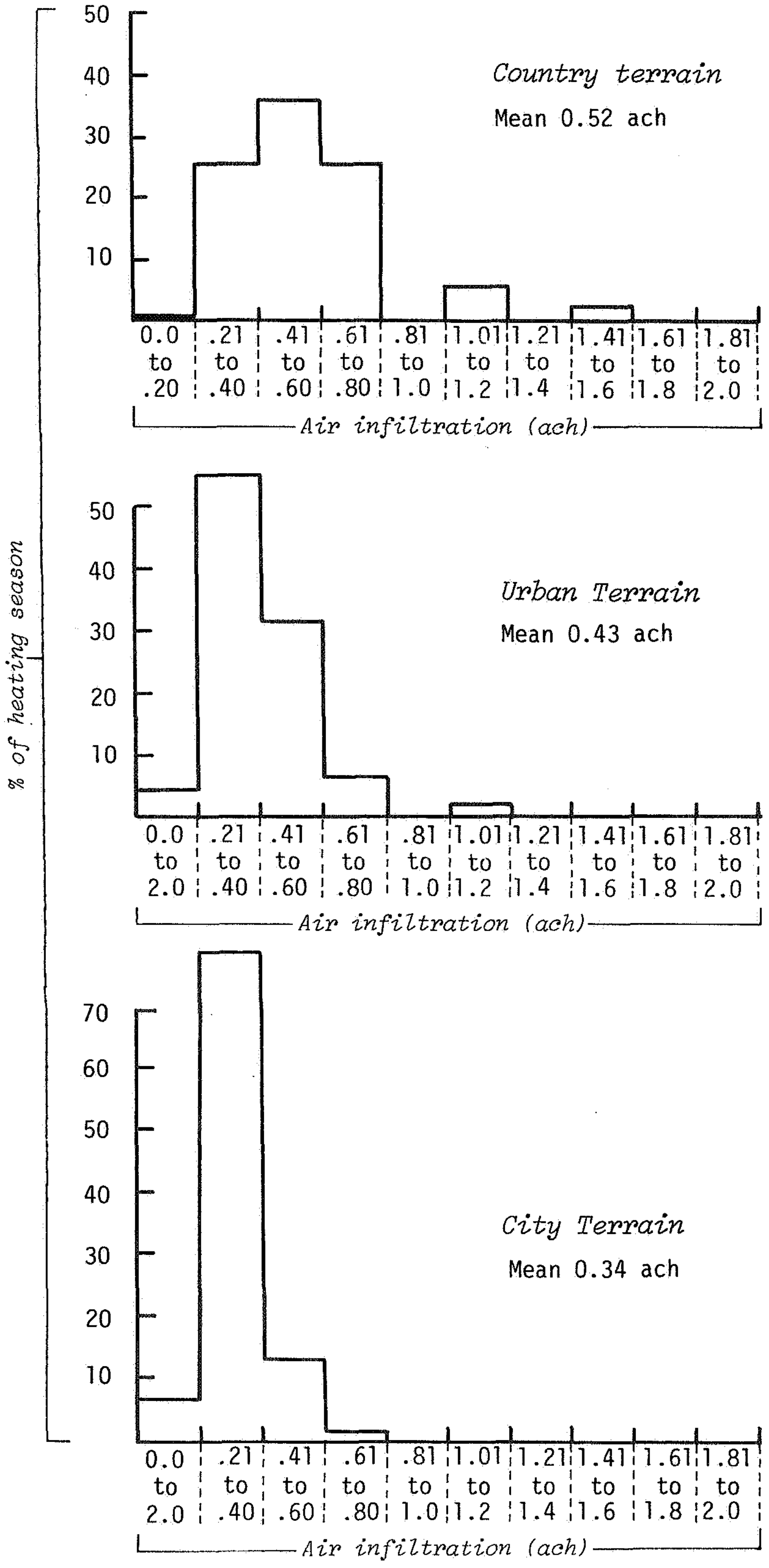
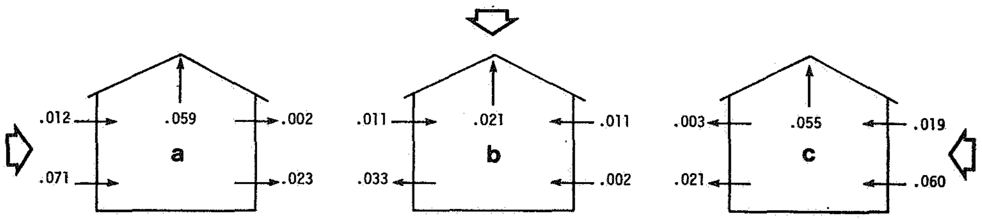


FIGURE 5 Frequency of air infiltration rates throughout heating season



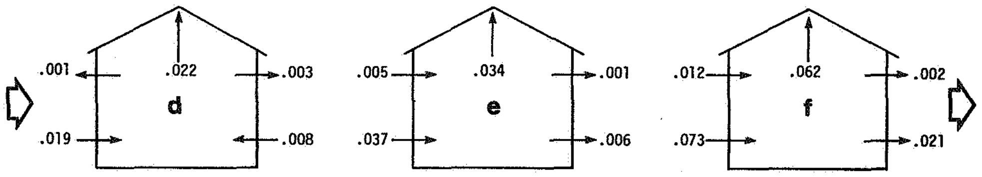
# FIGURE 6 Air flow patterns (all flows in $m^3s^{-1}$)

(i) Natural ventilation, wind dominated (10ms $^{-1}$ $\Delta T = 0^{\circ}C$)



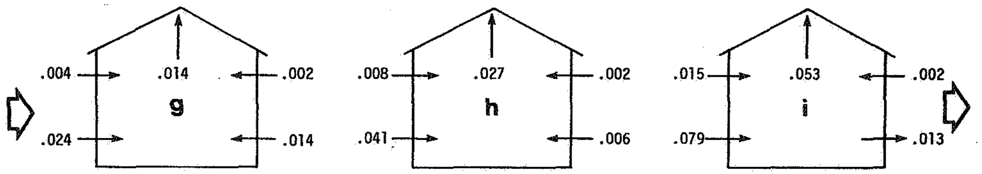
(ii) Natural ventilation, wind and stack

wind 2ms $^{-1}$ $\Delta T = 20^{\circ}C$ wind 5ms $^{-1}$ $\Delta T = 20^{\circ}C$ wind 10ms $^{-1}$ $\Delta T = 20^{\circ}C$



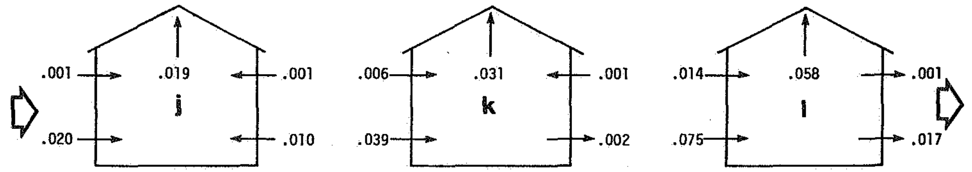
(iii) Mechanical exhaust ventilation 0.5 ach

wind 2ms $^{-1}$ $\Delta T = 20^{\circ}C$ wind 5ms $^{-1}$ $\Delta T = 20^{\circ}C$ wind 10ms $^{-1}$ $\Delta T = 20^{\circ}C$



(iv) Mechanical exhaust ventilation 0.2 ach

wind 2ms $^{-1}$ $\Delta T = 20^{\circ}C$ wind 5ms $^{-1}$ $\Delta T = 20^{\circ}C$ wind 10ms $^{-1}$ $\Delta T = 20^{\circ}C$



*Key:* ⇨ *wind direction* → *direction of air movement* ($m^3s^{-1}$)

FIGURE 7 Energy analysis of ventilation systems