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Modelling of Air Infiltration in Single- and Multi-cell Buildings*

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SUMMARY

The basic features of air infiltration models are summarized. The sources of error and the sensitivity of the models to these sources are described. An indication is given of the level of accuracy which can be expected under various conditions.

1. INTRODUCTION

Convective heat losses arising from infiltration and ventilation can be a large proportion of the total heat loss from a building. It is therefore important to be able to take account of this in a building simulation model. The aims of this short paper are to summarize air infiltration models, to describe their sensitivity to assumptions and/or data input errors and to indicate the levels of accuracy which can be expected.

There are important restrictions to the scope of the paper which should be noted. It concerns models which only predict the flow rates through openings in the envelopes of the building, i.e., essentially the net flow rates of air into and out of a cell. It makes no reference to models which simulate the air movement within the cells. The basic reason for this is that the pressure differences associated with internal air motion are usually small compared to the pressure differences generated by the wind and the buoyancy of the internal air. This means that the flow rates through the openings can be calculated without knowledge of the internal air movement (the converse is not necessarily true), which considerably simplifies the problem. Internal air motion can of course lead to temperature gradients within a cell, which can influence the convective heat loss directly (by altering the temperature of the outgoing air) and indirectly (by altering the hydrostatic pressure gradient). However as far as the ventilation heat loss is concerned, these are often secondary effects, and the first need is to predict the flow rates of the outgoing air. The models discussed below are intended purely for this purpose. They are very empirical, when compared to general numerical models which solve the partial differential conservation equations of three-dimensional flows. However complex models of this type cannot be justified unless the geometry and position of openings can be specified in detail, and this is generally not possible with the type of openings associated with infiltration. A more immediate application of such models is for calculating the external surface pressures on the envelope generated by the wind. At present however it is usually much easier to obtain this information from wind tunnel tests.

Except where stated otherwise, the paper is concerned only with the prediction of time-mean flow rates through adventitious openings i.e., infiltration. Air flow through purpose-provided openings (i.e., ventilation) is much easier to treat, because the size and the position of these openings will be known, and so the only reference to this will be in Section 4 where the accuracy of models is discussed. The restriction to time-mean flows is really a consequence of the fact that all available models are based on the assumption of quasi-steady flow. This is a necessary and justifiable assumption for an engineering approach to the problem, although, as will be

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mentioned, it does not mean that fluctuating air flows should be entirely neglected.

For reasons of brevity, emphasis will be placed on total infiltration rates rather than individual room rates, because the former are generally considered more important.

2. SUMMARY OF METHODS

The problem of predicting air infiltration can be expressed as follows. For a given building, and knowing the meteorological conditions and internal temperatures, what is the total flow rate into the building?

To predict the flow rate, it is necessary to specify the following information:

- the external surface pressures, generated by the wind;
- the internal surface pressure gradients, generated by buoyancy;
- the geometry of all openings (i.e., their size and shape);
- the position of the openings (i.e., the opening distribution).

Whether or not these four areas are considered as data or as part of the infiltration model will depend on whether the information is to be obtained separately (e.g., by measurement) or is incorporated in the model in the form of assumptions. In either case the predictions of the model will be sensitive to errors in the information and this sensitivity will be considered in Section 3.

In addition to the above it is necessary to have an equation which relates the flow through an opening to the pressure difference across the opening and its geometry. This equation is the crux of the infiltration model. In conventional fluid mechanics terms, one needs an equation which gives the discharge coefficient of the opening as a function of the Reynolds number of the flow through it, i.e.,

$$C_D = f(Re) \tag{1}$$

where f depends only on the shape of the opening.

This simple formulation is rarely seen explicitly in infiltration models, because it is common practice to use dimensional equations obtained from experimental measurements. These equations relate the flow rate through an opening q directly to the pressure difference across it, Δp, with coefficients based on experimental results. The most common equation is the so-called power law

$$q = c\Delta p^n \tag{2}$$

where c and n are the coefficients, but there is also support for the quadratic form

$$\Delta p = aq^2 + bq \tag{3}$$

where a and b are the coefficients.

Both equations give accurate curve-fits to leakage measurements, but such measurements are normally made at much higher pressures than those associated with natural infiltration. At low pressures, differences between the two equations become apparent. These differences are not trivial, because they can easily exceed 20% (see ref. 1). Moreover they are essentially systematic, and should be capable of being resolved more easily than some of the sources of error discussed in the next Section.

3. SENSITIVITY OF MODELS

For each of the four areas listed above, a brief description is given in the following of how the required information is usually specified, either from measurements or by assumptions incorporated in the model. This is followed by a discussion of the sensitivity of predictions to errors in the measurements or the assumptions. Calculations with the British Gas single-cell model VENT 2 [2] will be used for illustration. For a hypothetical terraced house with openings only on two walls, the solutions of the model can be represented by the functional relationship

$$\frac{Q}{C_{D\infty}AU_B} = f\left(\frac{\Delta C_p}{A_r^2}, \frac{C_{D\infty}}{Re_L}\right) \tag{4}$$

where the function f depends only on the distribution of the openings. The three non-dimensional parameters are:

$\dfrac{Q}{C_{D\infty}AU_B}$	dimensionless infiltration rate
$\dfrac{\Delta C_p}{A_r^2}$	ratio of wind and buoyancy pressures

$\frac{C_{D\infty}}{Re_L}$ discharge coefficient and house leakage Reynolds number.

All of the terms are defined in the List of Symbols. Here it can be noted that the infiltration rate of the building is denoted by Q and occurs only in the first parameter. The parameter $\Delta C_p/A_r^2$ depends only on the building height, temperature conditions and wind speed and direction. The parameter $C_{D\infty}/Re_L$ depends only on the leakage characteristic of the building, building height and temperature difference. A typical set of solutions to eqn. (4) can be seen in Fig. 2, which will be discussed in Section 3.4.

3.1. External surface pressures

The simplest way of specifying external pressures is to refer to tabulated wind tunnel data. A common assumption is that the pressure is uniform on any given surface, so that for a terraced house there are two wall pressures of interest, p_1 and p_2. As far as infiltration is concerned, it is the difference $(p_1 - p_2)$ which matters and this can be expressed in terms of the coefficient ΔC_p and a reference wind speed U_R

$$p_1 - p_2 = \tfrac{1}{2}\rho U_R^2 \Delta C_p$$

where ρ is air density. Wind tunnel data will generally be tabulated in such a way that ΔC_p can be readily obtained for a particular wind direction. The values of ΔC_p found in this way will not be without error, and there will also be errors arising from the fact that the values of wind speed and direction for the building in question will probably not correspond directly to the reference velocity measured in the wind tunnel. A fuller discussion of these errors is given in ref. 3, where the sensitivity of infiltration rate to errors in the specification of $(p_1 - p_2)$ is illustrated.

For the total infiltration rate of the building, the sensitivity depends very much on the value of the parameter $\Delta C_p/A_r^2$. Roughly speaking, when $\Delta C_p/A_r^2 < 2$ the sensitivity is very small, because buoyancy pressures are significant. At higher values than 2, wind pressures begin to become dominant and an error in $(p_1 - p_2)$ will lead to a similar error in Q. For room infiltration rates the situation is more complex and the sensitivity can exist at low values of the pressure ratio. This is simply due to the fact that the pattern of infiltration can change, with only a relatively small change in the total infiltration rate.

Finally, mention should be made of infiltration associated with pressure fluctuations arising from wind turbulence. Most models (with the exception of VENT) neglect this entirely. This assumption will be valid at low wind speeds, but otherwise errors could be significant, particularly when the wind direction or the building environment is such that ΔC_p is low.

3.2. Internal surface pressure gradients

The vertical pressure gradient in a space is determined by the density, and if the internal temperature is uniform the resulting pressure difference is obtained simply from a knowledge of the temperature difference between the room and ambient air. Specification of temperature difference generally creates relatively few problems since ambient temperature is known from meteorological data and internal temperatures are calculated in the building simulation model.

It is also relatively simple to treat the internal pressure gradient in a rigorous manner in the model, so that the interaction between wind pressures and buoyancy is properly accounted for. Some models however obtain the infiltration rate when wind and buoyancy act together from simpler calculations of the infiltration rates when wind and buoyancy act alone. There is evidence [4] that this simplification does not generally introduce large errors. It cannot be used for room infiltration rates however.

The sensitivity of infiltration rate to errors in temperature specification is in many respects the reverse of that for wind pressures. At values of $\Delta C_p/A_r^2$ greater than 2 (approximately) the sensitivity becomes low for total infiltration. Room rates can remain sensitive up to much higher values, but one cannot generalize because it depends on the leakage distribution of the building in question.

3.3. Geometry of openings

The specification of the geometry of openings is probably the area which has received most attention, albeit indirectly, because the geometry (i.e., size and shape) determines the leakage characteristic. Indeed it is common practice to refer to leakage characteristics of openings rather than their geometry, because the former are much easier to measure. This practice will be adopted here and for simplicity we will consider only the leakage characteristic of the whole building. A characteristic shows how the air leakage Q_L varies with an applied pressure difference Δp_L. The pressure is almost invariably applied by means of a large fan, and for small buildings values of Δp_L from 10 to 60 Pa are generally obtained. Figure 1 shows the form that a measured leakage characteristic might take.

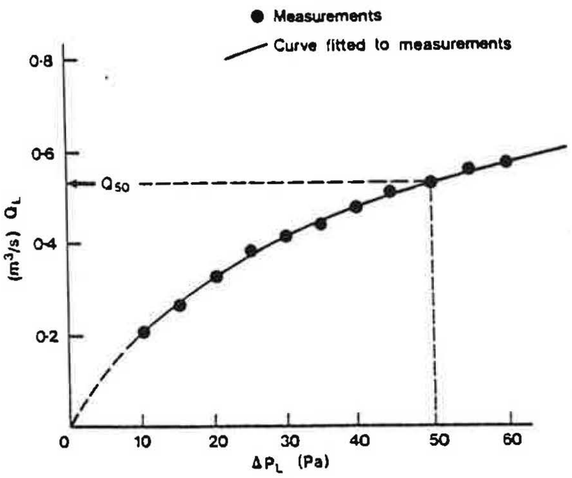

Fig. 1. Typical leakage characteristic.

When a quadratic equation is fitted to the measurements

$$\Delta p_L = aQ_L^2 + bQ_L \tag{5}$$

the characteristic is totally defined by the two coefficients a and b. It is generally preferred however to refer to the leakage at 50 Pa, Q_{50}, when assessing the leakage of a building, and in this case the second parameter will be the shape factor a/b^2. (If the power law is used the equivalent parameters are Q_{50} and n).

The most accurate way to specify Q_{50} and a/b^2 is to carry out a pressurization test. If this is not possible an estimate of the leakage through component openings (cracks in windows and doors) can be obtained from measurements of crack geometry. Unfortunately background leakage openings cannot generally be treated in this way and these openings are often the major source of adventitious leakage. Of course, if the building has not been constructed, neither of these approaches can be considered. One is then faced with the difficulty and uncertainty of estimating leakage from a knowledge of the proposed building construction. This approach is in its infancy although at least one attempt has been made [5]. Perhaps the best that one can hope for is to be able to predict the probability that the leakage will lie within a certain range. A prerequisite for this approach is the collection of a representative amount of leakage data followed by statistical analysis. Developments along these lines are in progress.

Not surprisingly the sensitivity of infiltration rate Q to Q_{50} is high. When a/b^2 and all other variables except Q_{50} are kept constant, the values of $C_{D\infty}/Re_L$ and $\Delta C_p/A_r^2$ are fixed and the solution to eqn. (4) is given by a fixed point on one of the curves in Fig. 2, i.e.,

$$\frac{Q}{C_{D\infty}AU_B} = \text{constant}$$

From the definitions of $C_{D\infty}A$ and U_B given in the Appendix and eqn. (5),

$$Q = Q_{50}\sqrt{\frac{\rho}{2(50 - bQ_{50})}} \times \text{constant}$$

which means that Q is approximately proportional to Q_{50}, and a given error in Q_{50} will lead to an error of similar size in Q. (In the limits when either $a = 0$ or $b = 0$, Q is exactly proportional to Q_{50}, as can be deduced from Fig. 13 of ref. 2.)

The sensitivity of Q to errors in a/b^2 is more complex, but fortunately the values of a/b^2 will in practice lie within a limited range, and this will impose an upper limit to errors in Q.

The above comments apply to room rates insofar as a change in Q_{50} will be accompanied by qualitatively similar changes. However there will be differences between the responses of each room, depending on where their flow rates lie on their leakage characterictics.

3.4. *Distribution of openings*

The specification of the distribution of the adventitious openings is without doubt a difficult task. This is due to the fact that the distribution is not easy to measure. It can be done on a room-by-room basis [6] and sealing of components will provide more detailed

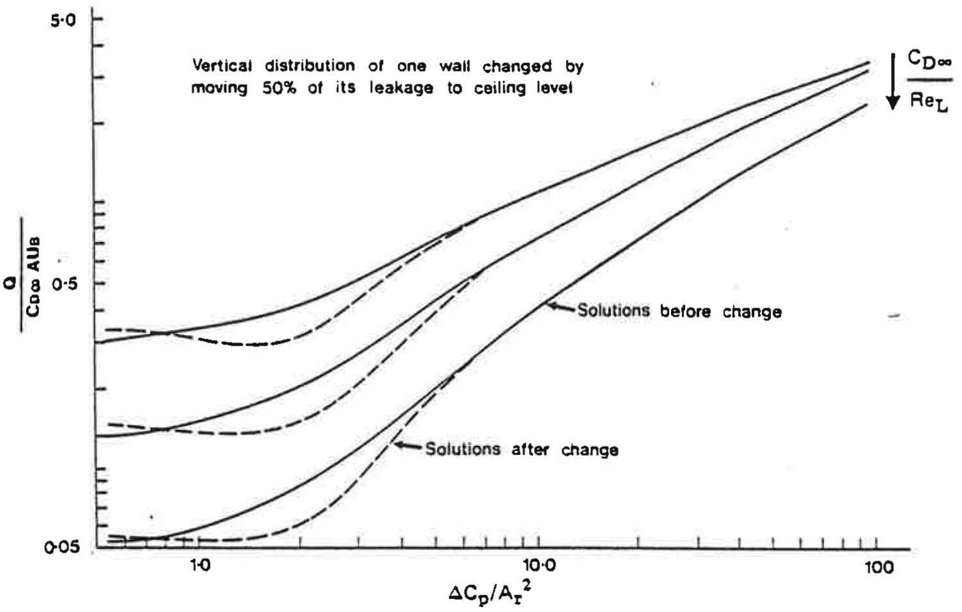

Fig. 2. Effect of changing the vertical distribution of leakage.

information, but these techniques are laborious and do not provide all the information required. There is a consequent lack of data available which means that a prediction of the distribution (e.g., at the building design stage) is even more imprecise than the prediction of the leakage Q_{50}.

As a result of these problems it is common for infiltration models to have built-in assumptions about the distribution. One such assumption is that the openings on a wall (or the leakage) are uniformly distributed. This will be referred to here as a uniform vertical distribution of openings. Another assumption is that the distribution of openings between walls (the wall distribution) is fixed. The errors which these assumptions introduce can be investigated with VENT2 because both the vertical and the wall distribution can be varied in the model. A non-dimensional presentation of the solutions of the model is particularly beneficial here, because changing the distribution only affects the function f in eqn. (4), as shown in Figs. 2 and 3.

Figure 2 shows the effect of changing the vertical distribution on one wall. The effect is negligible when wind pressures dominate ($\Delta C_p/A_r^2 > 10$) and this is to be expected, because the wind pressure is assumed to be constant on each wall. At lower values of $\Delta C_p/A_r^2$ differences of 50% or more are apparent, particularly in the range $1 < \Delta C_p/A_r^2 < 3$ where there is a strong interaction between wind and buoyancy.

Figure 3 shows the effect of a change in wall distribution. This is limited to moderate values of $\Delta C_p/A_r^2$ (1 to 10) and the difference between the two cases rarely exceeds 30%. This behaviour is expected, because when buoyancy is dominant only the vertical distribution of openings is important. When wind pressures are dominant it is the pressure difference $(p_1 - p_2)$ which matters, rather than the values of p_1 and p_2, so it is of no consequence whether the larger number of openings occurs on the windward or leeward wall. (This is only true for the simple terraced house considered here).

From the above it can be seen that assumptions concerning the leakage distribution on walls can be made which do not introduce large errors in Q. However no consideration has been given in the above to the question of ceiling leakage. The prediction of Q will tend to be very sensitive to assumptions made about the leakage of the ceiling which is adjacent to the roof (as distinct from internal ceilings). The reason for this is that an opening in the ceiling will be subjected to maximum buoyancy pressures (by virtue of its height) and to relatively large wind pressures acting in the same direction (roof pressures

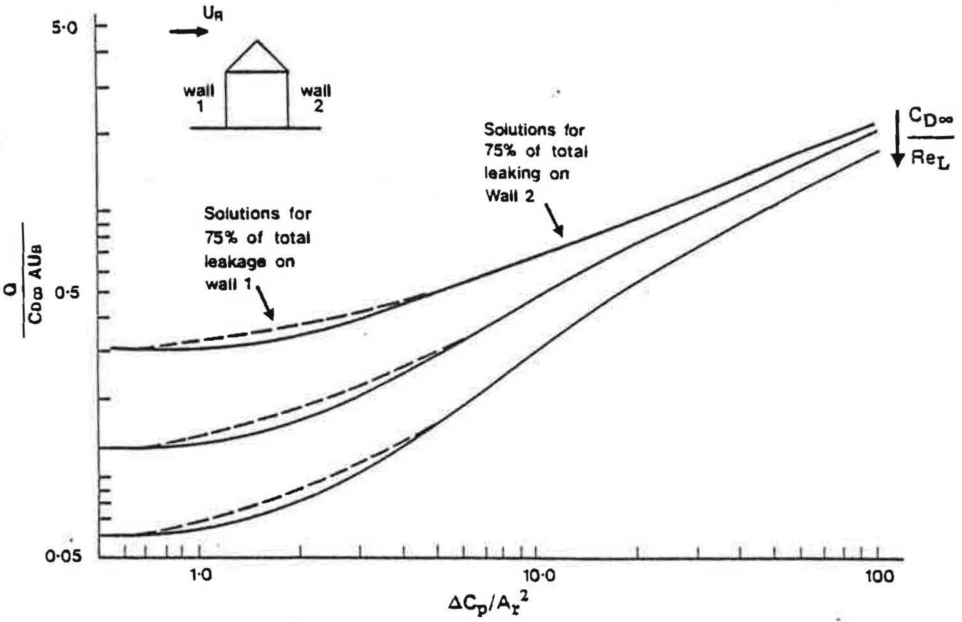

Fig. 3. Effect of changing wall distribution of leakage.

will tend to be negative). As a result of this, the infiltration rate can be much more sensitive to ceiling leakage than to wall leakage.

Clearly room infiltration rates are much more sensitive to errors in the leakage distribution. A good illustration of this can be found in ref. 7, where predictions of whole-house and room rates are compared. The relatively poor prediction of room rates is almost certainly due in part to errors in the leakage distribution.

4. ACCURACY OF MODELS

From the foregoing it will have been seen that the accuracy of an infiltration model depends on many factors. The sources of error can be loosely grouped as follows.

Sources which can be significant under most or all weather conditions are

• flow equation	(±50%)
• leakage at 50 Pa	(no limit)
• shape of leakage characteristic	(±50%)

Sources which can be negligible under certain weather conditions are

• pressure coefficient (ΔC_p)	(±30%)
• reference wind speed	(±30%)
• air temperatures	(±20%)
• leakage distribution (walls)	(±30%)
• leakage distribution (ceilings)	(±100%)
• neglect of pressure fluctuations	(−30%)

To give some idea of the relative importance of the sources of error, the figures in brackets are given as a guide to the potential maximum error which might arise from each source. It must be emphasised that these figures are very approximate and are only intended for ranking the sources of error.

One can obtain a good estimate of the minimum error which can be achieved with models from the various validation exercises which have been carried out (e.g., refs. 7 - 9). The indication from these is that an error less than ±25% can generally be expected for the total infiltration rate. It should be noted however that a definite validation exercise, in which all the required information is rigidly and accurately specified, has yet to be made. For room rates there are few published results, but ref. 7 is an example.

When a model is used under less ideal circumstances the potential errors are larger. This is especially true when the leakage at 50 Pa cannot be measured. It should however generally be possible to make an estimate of the likely range of Q_{50} (e.g., from measurements on similar buildings) and this can be used to give an indication of the errors in the predicted infiltration rate.

It is necessary to conclude this discussion of accuracy with a point which cannot be overemphasized. So far we have considered only errors in infiltration rates. If the building in question has purpose-provided openings (or mechanical ventilation) the errors in the total flow rate (infiltration plus ventilation) could be much lower than with infiltration alone. The reason for this is that the flow through purpose-provided openings is much easier to predict. Virtually all of the sources of error listed above are much reduced in importance, provided that the model can treat such openings separately from adventitious openings. VENT2 has this facility and it is an important one (see ref. 10) if the greatest accuracy is to be achieved.

5. CONCLUSIONS

Infiltration models are distinguished by the basic flow equation which they use and especially by the assumptions which they make about the information needed to solve the equation.

The sources of error in the predictions are many and varied. Some sources of errors can be significant under all conditions of use (i.e., the flow equation and the leakage characteristic), while others can be negligible under certain weather conditions. The potentially greatest source of error is the leakage. At best, one can expect the error in infiltration rate to be less than ±25%. If the leakage of the building cannot be measured, much larger errors can be expected.

The presence of purpose-provided openings in a building can significantly reduce errors, when the flow through these openings (ventilation) is large in relation to the infiltration through the adventitious openings. This benefit will only be fully realized if the model in question treats the two types of opening separately.

LIST OF SYMBOLS

a, b	coefficients in leakage characteristics, eqn. (3)
A	effective total area of openings
A_r	Archimedes number, $A_r \equiv U_B/U_R$
$C_{D\infty}$	discharge coefficient of openings at very high flow rates (see Appendix), $C_{D\infty} = \sqrt{\rho/2a}/A$
ΔC_p	coefficient of surface pressure difference due to wind, $\Delta C_p = (p_1 - p_2)/\frac{1}{2}\rho U_R^2$
$\Delta\rho$	difference between internal and external air densities
g	gravitational acceleration
h	height of building to upper ceiling
Q	infiltration rate
ρ	density of external air
Re_L	leakage Reynolds number (see Appendix), $Re_L \equiv \rho U_B/bA$
U_B	equivalent air speed of buoyancy pressure difference, $U_B \equiv \sqrt{\Delta\rho g h/\rho}$
U_R	reference wind speed

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APPENDIX

It should be noted that the values of A, $C_{D\infty}$ and Re_L cannot normally be determined. For the purposes of evaluating Q using a measured leakage characteristic it is sufficient to know the values of $C_{D\infty}A$ and $C_{D\infty}/Re_L$. These can be found from:

$$C_{D\infty}A = \sqrt{\rho/2a}$$

$$C_{D\infty}/Re_L = \frac{1}{U_B}\sqrt{\frac{b^2}{a}\,\frac{1}{2\rho}}$$