Ventilation Measurements at Model Scale in a Turbulent Flow

D. W. ETHERIDGE*
J. A. NOLAN†

Ventilation rates have been measured in a model building in a wind tunnel. Two types of opening, circular holes and model windows, have been tested under two wind conditions. One wind condition was selected to give the maximum flow through the model, while for the other condition the ventilation was due mainly to turbulent pressure fluctuations. The different characteristics of the two types of opening are illustrated. Comparisons are made between the measurements and thoeretical predictions. The use of wind tunnels for ventilation studies is discussed.

INTRODUCTION

IT IS well known that the ventilation which arises from the action of the natural wind on the cracks around doors and windows of dwellings (as distinct from less well-defined cracks in floors and walls) can provide a large proportion of the total ventilation of a dwelling.

An important technique for investigating the effect of the natural wind on ventilation is wind tunnel testing. However (see, for example [1]) even for crack sizes that are encountered at full-scale, the flow through the cracks is Reynolds number dependent. Setting aside the practical problems of modelling cracks in small models, it is clear that the presence of scale effect will create problems in the extrapolation of ventilation rates measured in small models to the full-scale situation. This is therefore a strong argument against the use of ventilation rate measurements in wind tunnel models. A possible means of partially overcoming this problem is to simulate the actual full-scale cracks by circular holes. This method could probably be used to reproduce the behaviour of the full-scale cracks at high Reynolds number, provided that the area of the holes is correctly determined.

However, in view of the problem of scale effect, a potentially better approach is to use wind tunnels to measure the pressure distribution generated on the surface of the model building in question and then to use this as data for a theoretical prediction of ventilation rates. There is a problem to be overcome with this technique, which is the ventilation which arises directly from the action of turbulent pressure fluctuations [2]. At the present time theoretical methods for predicting ventilation rates in dwellings can not account for this source of ventilation. They account only for the ventilation due to steady pressures acting across openings. This inadequacy of theoretical methods can be used as an argument in favour of ventilation measurements in models, because such measurements will include the effects of turbulence. In fact if the effects of turbulence were large enough it might be preferable to use wind tunnel models for measuring ventilation rates rather than pressure distributions.

The prime objective of the work described here was to investigate the relative magnitudes of the ventilation due to steady pressures and to fluctuating pressures. This has been done by measuring ventilation rates in a simple model building for two conditions. In the first condition the ventilation due to steady pressures is at a maximum. In the second condition the ventilation due solely to the action of fluctuating pressures is at a maximum. These measurements have been carried out for model windows with scaled cracks and for simple circular holes, in order that their flow characteristics under the two conditions can be compared.

Ventilation induced solely by turbulent pressure fluctuations has been investigated by several authors [2–4]. In his early paper, van der Held [2] discusses both ventilation flows and the effects of turbulence in detail. The presence of scale effect is implicit in his flow equations, but this effect is not investigated, and for his calculations of turbulence induced ventilation he makes simplifications concerning the form of these equations and the nature of the pressure fluctuations. The theory indicates that the ventilation rate attributable directly to turbulence decreases to zero as the time-mean pressure difference, $\overline{\Delta p}$, across the opening increases from zero. This is what one would physically expect. As $\overline{\Delta p}$ is increased, a point is reached where there is no change in direction of flow through the opening, due to the pressure fluctuations, $\Delta p'$. The instantaneous pressure difference across the opening, Δp, is throughout this present paper assumed to be given by the sum of mean and fluctuating components,

$$\Delta p = \overline{\Delta p} + \Delta p'.$$

Although van der Held's work is of considerable value, he does not give any experimental measurements. Malinowski [3] however presents experimental results obtained from tests on different arrangements of circular holes on one face (forming the wind tunnel

---

*British Gas Corporation, Watson House, London SW6 3HN, U.K.

†Vacation Student, Kingston Polytechnic, Surrey, U.K.

2.4. *Wind velocity profiles*

A non-uniform mean velocity profile was generated in the wind tunnel by means of a grid of horizontal slats across the working section. Figure 2 shows the profiles obtained at two wind speeds and it can be seen that the shape of the profile is reasonably independent of wind speed. A power law profile with exponent 0.23, is shown for comparison, i.e.

$$\frac{U}{U_{\text{ref}}}=\left(\frac{H}{H_{\text{ref}}}\right)^{0.23},$$

where H denotes height above the tunnel floor. The measurements were made with a pitot-static tube, micromanometer and d.v.m. (see 2.5). Rough estimates of the turbulence level of the streamwise velocity were made from the root-mean-square of the dynamic head fluctuations and the corresponding profiles are also given in the figure.

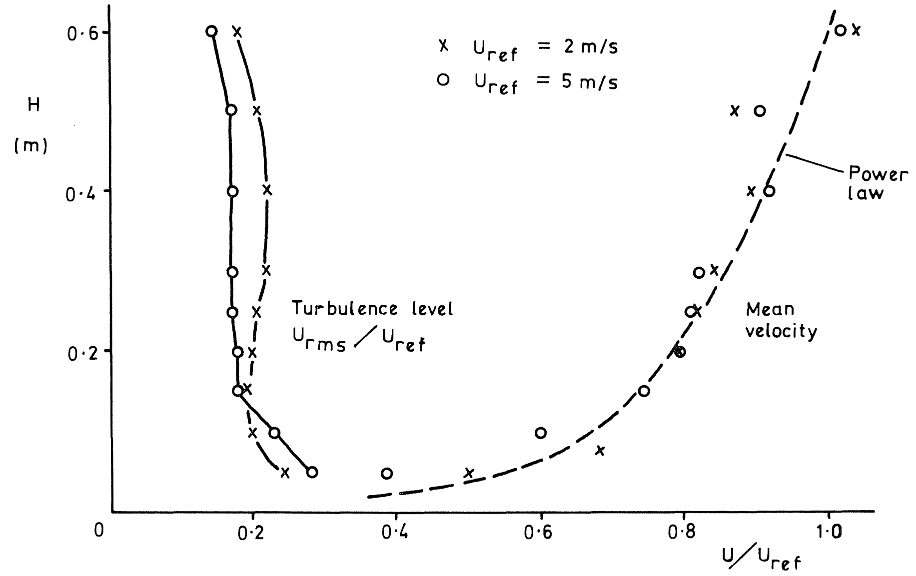


Fig. 2. Mean velocity and turbulence intensity profiles at two wind speeds.

The turbulence generated by the grid cannot be considered as completely representative of that encountered in the real wind. For example the scales of the grid turbulence will tend to be small in relation to the model. However the model will generate its own turbulence and this should be reasonably representative of full-scale buildings. Thus although the present wind-tunnel does not allow complete simulation of the full-scale wind, it probably gives a better simulation than that described by Malinowski [3].

2.5. *Pressure measurements*

To allow theoretical predictions of the ventilation flow rates through the model windows, measurements were made of the pressure difference acting across the centre point of the windows. The instantaneous value of this pressure is denoted by Δp, and since Δp is a stationary random variable we can put $\Delta p=\overline{\Delta p}+\Delta p'$, where $\overline{\Delta p}$ is the mean value and $\Delta p'$ is the fluctuating component. Measurements were made of $\overline{\Delta p}$ and $\overline{\Delta p'^2}$ using a Furness micrometer and a digital voltmeter (Solartron Time Domain Analyser JM 1860). It must be noted that the values of $\overline{\Delta p'^2}$ obtained in this way are underestimates because of attenuation of the high frequency components of Δp. Although the pressure tubing was made as short as possible to minimise this, the micromanometer does not respond to frequencies greater than 200 Hz and attenuation occurs at lower frequencies. However since most of the turbulence energy will occur at frequencies much lower than 200 Hz the underestimation should be small.

In addition, a false window with tappings distributed around its perimeter was used to measure the mean difference between the pressure at the centre of the window and the pressure around its perimeter.

2.6. *Scope of tests*

Each pair of windows and each pair of circular holes has been tested over a range of wind speeds (1.5–7 ms^{-1}) at two angles of incidence to the wind direction. The effective ventilation rate of the model was measured.

The object of measuring over a range of wind speeds was to determine any scale effects. The object of using two angles of incidence, α, was to obtain some idea of the relative magnitudes of ventilation due to mean pressure differences and to pressure fluctuations. Figure 3 defines the two values of incidence used. At $\alpha=0°$ the ventilation due to mean pressure difference $\overline{\Delta p}$ is at a maximum because $\overline{\Delta p}$ is at a maximum. At $\alpha=90°$, $\overline{\Delta p}$ is theoretically equal to zero and the ventilation is due to pressure fluctuations.

3. PRESENTATION OF RESULTS

3.1. *Ventilation rates*

The effective ventilation rate results are presented mainly as plots of V_e/AU_{ref} against U_{ref}. This form of

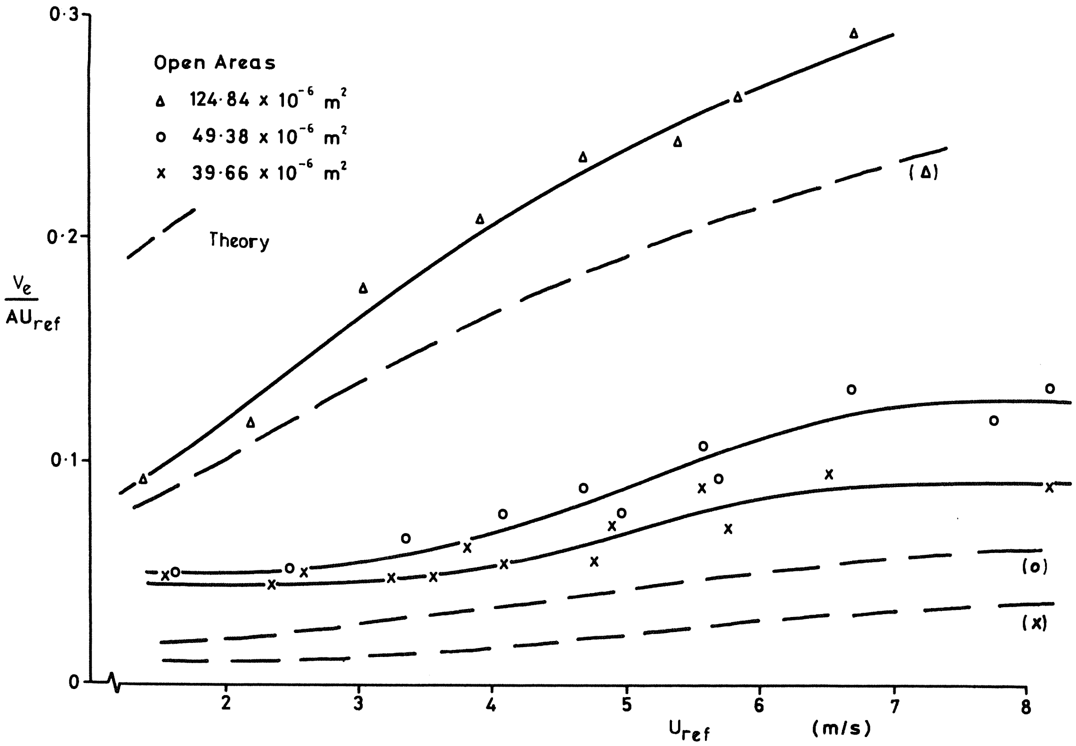


Fig. 6. Nondimensional ventilation rates with model windows and comparison with theory, $\alpha=0°$.

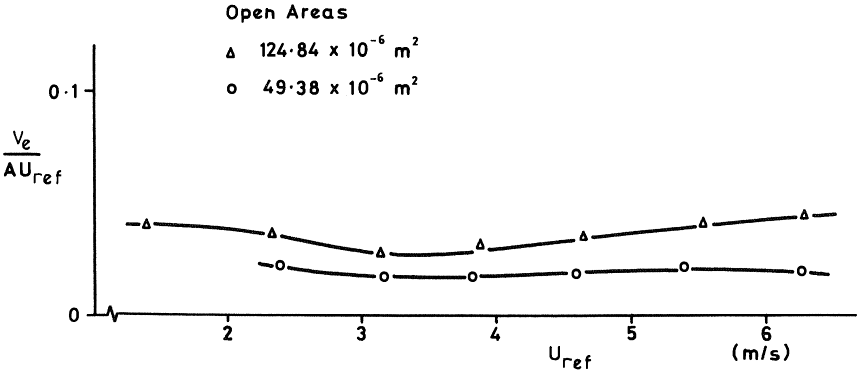


Fig. 7. Nondimensional ventilation rates with model windows, $\alpha=90°$.

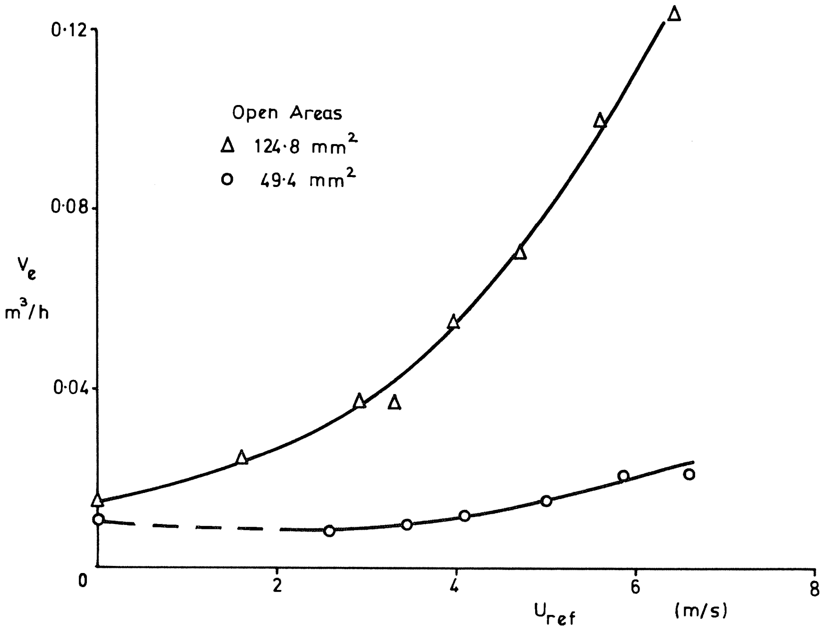


Fig. 8. Ventilation rates with model windows, $\alpha=90°$.

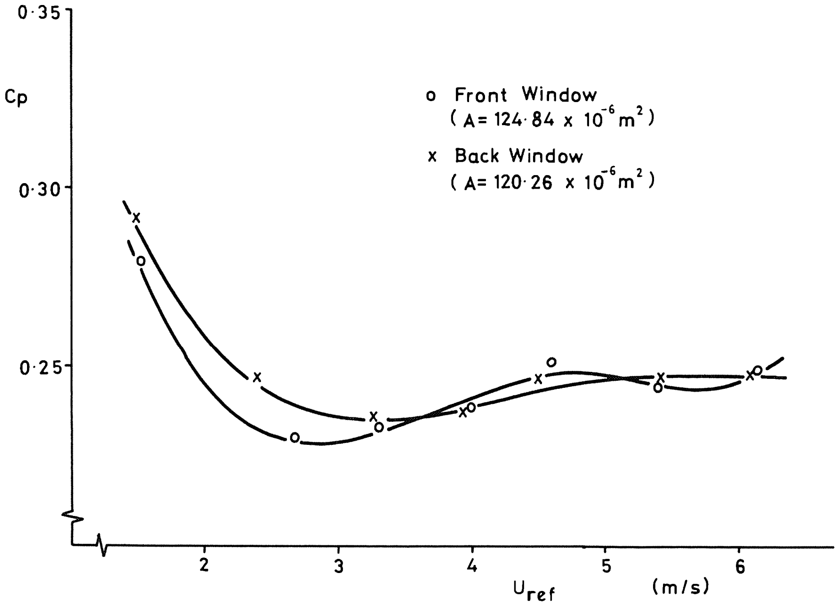


Fig. 11. Coefficient of pressure difference across large windows, $\alpha = 0°$.

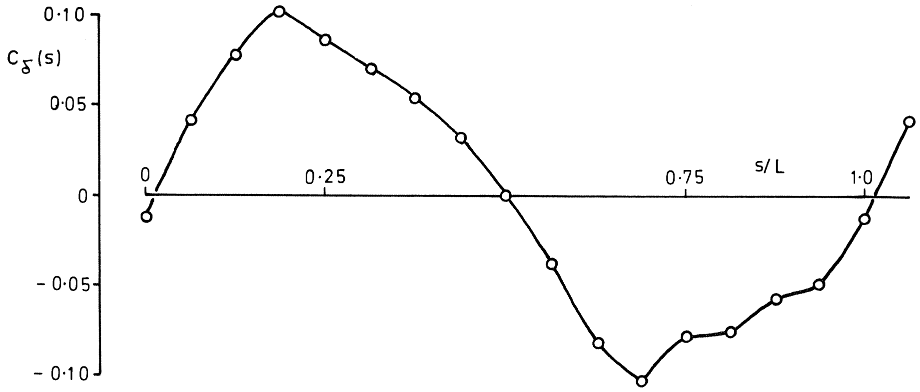


Fig. 12. Coefficient of pressure difference between the centre of the window and points on the perimeter, $\alpha = 0°$.

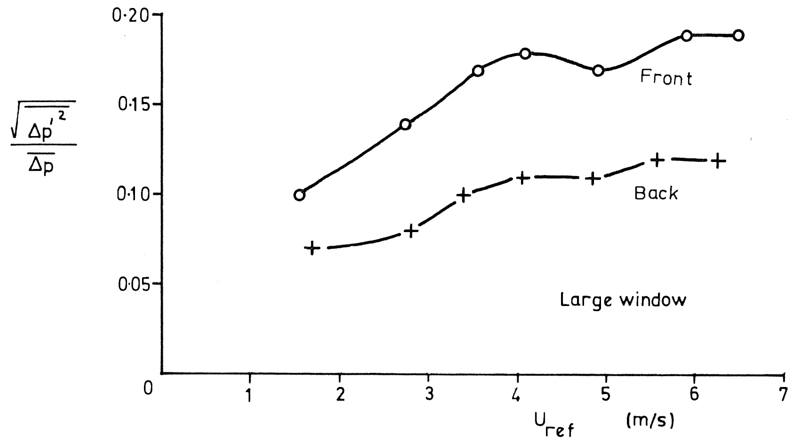


Fig. 13. Normalised root-mean-square of the fluctuations in pressure difference across window, $\alpha = 0°$.

Comparisons have not been made for the smaller open areas because there is some doubt that the ventilation mechanisms are due solely to turbulence (see the discussion of Fig. 8 in Section 3.1).

In the second equation, L is the crack perimeter, z is the distance through the crack (see [1]), ρ is the air density and ν is the kinematic viscosity.

It must be remembered that the values of $\overline{|V'|}$ are likely to be underestimates because $\overline{\Delta p'^2}$ is underestimated (see 2.5).

5. DISCUSSION OF RESULTS

In the following the results for the circular holes and model windows are first discussed separately. Following this, in Section 5.3, the implications of the results to wind tunnel testing are considered.

5.1. *Circular holes*

The results for $\alpha=0°$ (Fig. 5) are essentially what one would expect for circular holes i.e. little variation of V_e/AU_{ref}. There is some variation with Reynolds number but the theoretical results show that some of this is due to variations in $\overline{\Delta p}$. A discharge coefficient of 0.65 was chosen for the theoretical calculations and this gives values of $\bar{V}/AU_{\mathrm{ref}}$ lying within about $\pm 15\%$ of the measured values. For the smallest hole, the variation of ventilation rate with U_{ref} extends over the complete range of U_{ref} but this is not unexpected because the Reynolds number of this hole will be less than half that of the largest hole.

Turning to the results obtained at $\alpha=90°$ it is apparent that there is a large amount of variation in the results for the two smaller holes, whereas the results for the largest hole are much less dependent on Reynolds number.

For the largest hole the ratio between the values of V_e/AU_{ref} at $\alpha=0°$ and 90° is about 5.8. This ratio is virtually independent of wind speed for speeds greater than $2\,\mathrm{ms}^{-1}$.

Because of the low values of V_e obtained with the smaller holes experimental errors are probably more significant, and so only the results for the larger holes have been compared with the predicted values of $\overline{|V'|}/AU_{\mathrm{ref}}$ (see Fig. 15). It can be seen that the qualitative behaviour of V_e/AU_{ref} and $\overline{|V'|}/AU_{\mathrm{ref}}$ is similar, but the former values are about 0.5 times the latter values. From his tests on a single circular hole of area $10.1\times10^{-6}\,\mathrm{m}^2$, Malinowski [3] obtained a value of 0.845 for the ratio of V_e/V_a where V_a is the 'actual flow through' the box, measured with a hot wire. It is not clear from [3] how V_a is related to $\overline{|V'|}$ and the large difference between the factors 0.845 and 0.5 could be due to this. Alternatively, the different model configurations and turbulence conditions could explain the difference. As demonstrated by Cockcroft and Robertson [4], the relative sizes of the opening and the turbulence length scales is important in determining the effective ventilation rate. From their tests on a single rectangular opening, they obtained values for the above factor of about 0.37. Again there are considerable differences between their experimental arrangement and the present one.

5.2. *Model windows*

The results for the model windows with $\alpha=0°$ illustrate the strong scale effect, particularly for the largest window. For this window the nondimensional ventilation rate increases by a factor of three for the range of tunnel speeds tested, and it appears that considerably higher tunnel speeds would have to be achieved for the dependence on Reynolds number to be small. The theoretical predictions for this window are qualitatively very good but there is a consistent underestimation of V_e/AU_{ref} of about 20%. For the smaller windows the underestimation is much larger. The reasons for this are not clear but there are several possibilities.

Firstly, it must be remembered that the crack flow equations [1] are approximate in nature. They were derived from measurements in steady flow on simulated full size cracks. Although they have been found to describe the steady flow through real doors and windows [1], virtually all of the present measurements on the two smaller windows were made at Reynolds numbers which lie outside the range over which the equations were derived. In contrast virtually all of the measurements on the larger window lie within the range and the agreement is correspondingly better. This explanation is not totally satisfactory however, because better agreement would be expected at the high wind speeds for the smaller windows.

Another possible explanation concerns the pressure distribution around the crack perimeter. Using the values of $C_\delta(s)$ given in Fig. 12 it is possible to construct the variation of the pressure difference across the crack as a function of s. The pressure difference across the crack $Cp(s)$ is given by

$$Cp(s)=Cp+C_\delta(s).$$

Taking 0.24 as the value for Cp, it can be seen that in the lowest part of the window $Cp(s)$ is relatively low (about 0.15). It is possible therefore that along this part the turbulent pressure fluctuations were large enough to cause reversal of flow through the crack. This would lead to ventilation which is not accounted for by the theory and thus it could explain the difference between prediction and measurement. However, measurement of the root-mean-square and the mean components of pressure at a point on the base of the window gave a ratio of the former component to the latter of about 0.35. For there to be significant flow reversal at this point the probability distribution of $\Delta p'$ would have to depart considerably from a Gaussian form.

Another point which has to be borne in mind is that the values of V_e have been calculated from decay rates on the assumption that at any instant of time the concentration of tracer gas within the model is uniform. It is well known that this assumption is only approximate and it is possible that non-uniformities existed flow rates measured at $\alpha=0^\circ$ and $\alpha=90^\circ$ has shown that the former flow rate is about six times larger than the latter for both types of opening. It is concluded therefore that wind tunnel models should generally be used for measuring external pressure distributions (for use in a theoretical prediction of ventilation rates) rather than for measurement of ventilation rates. There is however, some scope for the use of circular holes in models for measuring ventilation rates. To this extent, wind tunnels are a simple means of providing exploratory data for, say, full-scale investigations.

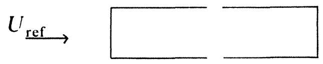
The effectiveness of turbulent pressure fluctuations for ventilating the model building has been investigated by comparing the measured effective ventilation rates, V_e, with the mean rate at which fresh air enters the building $\overline{|V'|}$. This latter rate has been calculated from measurements of the root-mean-square of the pressure difference across the openings, by assuming that the pressure has a Gaussian probability distribution. The effectiveness, $V_e/\overline{|V'|}$, was found to be about 0.5 for the circular hole and about 0.8 for the model window.

Acknowledgement—The permission of British Gas Corporation to publish this paper is gratefully acknowledged.

REFERENCES

1. D. W. Etheridge, Crack flow equations and scale effect. *Building and Environment* **12,** 181–189 (1977).
2. E. F. M. van der Held, Der Einfluss der Turbulenz auf die Luftung. *Gesundheits ingenieur* **74,** 381–385 (1953).
3. H. K. Malinowski, Wind effect on air movement inside buildings. *Proc. 3rd Int. Conf. on Wind Effects on Buildings and Structures*, Tokyo, pp. 125–134 (1971).
4. J. P. Cockcroft and P. Robertson, Ventilation of an enclosure through a single opening. *Building and Environment* **11,** 29–35 (1976).
5. R. E. Bilsborrow and F. R. Fricke, Model verification of analogue infiltration predictions. *Build. Sci.* **10,** 217–230 (1975).
6. D. E. Sexton, A simple wind tunnel for studying air flow round buildings. BRS Current Paper (1968).
7. J. Harris-Bass, B. Kavarana and P. Lawrence, Adventitious ventilation of houses. *Build. Serv. Engnr.* **42,** 106–111 (1974).
8. A. R. Stanley, Internal Communication, Mathematics Group, Watson House.

APPENDIX



Consider the case with $\alpha=90$ and assume that the flow is symmetrical so that the mean pressure difference $\overline{\Delta p}$ across each opening is zero. Thus for each opening we can put $\Delta p=\Delta p'$. The assumption of symmetry also means that the mean flow through each opening is zero, i.e. $\bar{V}=0$ and $V=V'$. The mean rate at which fresh air enters through one of the openings is given by $\overline{|V'|}/2$ i.e. one half of the mean of the modulus of V'. If perfect mixing occurred, the effective ventilation rate due to both the windows would be equal to $\overline{|V'|}$. By assuming quasi-steady flow through the openings it is possible to calculate $\overline{|V'|}$ from the measurements of the root-mean-square pressure difference across the opening. These calculated values can then be compared with the measured values of V_e.

Circular holes

Since quasi-steady flow is assumed we can put

$$V'=AC_z\sqrt{\frac{2}{\rho}}|\Delta p'|^{0.5}$$

and

$$\overline{|V'|}=AC_z\sqrt{\frac{2}{\rho}}\overline{|\Delta p'|^{0.5}}.$$

The problem is to relate

$$\overline{|\Delta p'|^{0.5}} \quad \text{to} \quad \overline{\Delta p'^2}$$

which has been measured. This has been done [8] by evaluating the expected value of $|\Delta p'|^{0.5}$ using Gamma functions, to give

$$(\overline{|\Delta p'|^{0.5}})^2=0.67598(\overline{\Delta p'^2})^{0.5}.$$

Hence

$$\overline{|V'|}=0.822AC_z\sqrt{\frac{2}{\rho}}(\overline{\Delta p'^2})^{0.25}.$$

Here, the instantaneous flow rate is denoted by V where $V=\bar{V}+V'$.

Model windows

From [1] the equation governing the flow through the window is

$$1.5V^2+95.7\frac{zL^2\nu}{4A}V=A^2\frac{2\Delta p}{\rho}.$$

At low flow rates, i.e. low values of Δp, this equation can be simplified to

$$95.7\frac{zL^2\nu}{4A}V=A^2\frac{2\Delta p}{\rho}$$