VENTILATION THROUGH OPENINGS ON ONE WALL ONLY

by P R Warren

SUMMARY

The main mechanisms giving rise to the natural ventilation of spaces with openings to outside air in one wall only are reviewed. Expressions which enable the magnitude of the ventilation rates due to each of these mechanisms to be calculated are derived from theoretical and wind tunnel studies. The results of measurements on a full-scale building are reported and compared with predictions.

August 1977
PD94/77

This paper is being offered for publication at the International Conference on Heat and Mass Transfer in Buildings being held on 29 August 1977 to 3 September 1977.

EDE22/70
A113/5/10

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NOMENCLATURE

A	area of opening (subscripts 1,2 see below) (m^2)
b	breadth of rectangular opening (m)
c	concentration (subscripts i,e)
f_1, f_2	functions of η
G	mass flow rate (kg/s)
g_1, g_2	functions of η_r
H	vertical distance between centres of two openings (m)
h	height of rectangular opening (m)
I	integral, defined in the text
k, k_p	wave number ($= n/U_R$; $= n_p/U_R$) (m^{-1})
n, n_p	frequency, frequency at peak value of pressure spectrum (Hz)
p	pressure (subscripts 1,2,R) (N/m^2)
$p', \hat{p}$	fluctuating component of pressure; rms value of p' (N/m^2)
U	mean velocity (subscripts L,R,T see below) (m/s)
u	velocity in x-direction within mixing layer (m/s)
V	volume (m^3)
v	velocity in y-direction within mixing layer (m/s)
Ar	Archimedes number ($=\Delta\theta gh/\theta U^2$)
Cd	discharge coefficient
Cp	pressure coefficient ($= (p-p_o)/\frac{1}{2}\rho_o U_T^2$)
F	flow number ($=Q/AU$) (subscripts L,R,T indicate U_L etc)
Gr	Grashof number ($= \Delta\theta gh^3/\theta\nu^2$)
M	aspect ratio of rectangular opening ($= h/b$)
Re	Reynolds number ($= UR/\nu$)

Nomenclature - continued

α	arbitrary constant relating to width of mixing layer
β	angle of flow direction in plane parallel to wall
γ	angle of wind direction (=0, perpendicular to wall)
Δ	difference between two values of same variable
ε	ratio of opening area (= A_1/A_2)
η, η_r	similarity variable; value of η in plane of opening
θ	absolute temperature (deg K)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ϕ	angle of opening of window 'vane'

SUBSCRIPTS

1,2	identification number of opening
i,e	value p and v at inner and outer edges of mixing layer
L,R,T	value of U, and dimensionless quantities Ar, F which depend upon U, local to the opening (L), at a chosen reference point remote from the building (R), and at a reference point in the free wind at a height equal to that of the building (T).
o	value of p and ρ taken for reference in defining Cp

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INTRODUCTION

Under the action of the steady pressures generated by wind and temperature differences, air flows through openings, both purpose-made and adventitious, in the outer skin and between spaces within a building. The general principles underlying this form of ventilation were stated many years ago (1,2) and have subsequently been developed and incorporated in computer-based methods for the prediction of flow through buildings consisting of complex arrangements of spaces (3,4). However there are situations when 'through' ventilation of this type cannot occur, in particular when a space within a building is well-sealed with respect to the rest of the building and has openings in one external wall only. Typical examples are cellular offices or classrooms in which internal doors are kept closed for reasons of privacy or noise, and for which the only large openings available for ventilation in summer are in the one external wall. Langdon and Loudon (5) have shown that such rooms tend to have higher summer temperatures and give rise to greater user dissatisfaction than through-ventilated rooms exposed to the same conditions of solar gain etc. The purpose of the work described in part in this paper is to provide a basis for the choice and sizing of openings to give the design summertime ventilation rate in rooms of this type.

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$$\frac{G}{\rho b h}\left[\frac{\theta}{gh\Delta\theta}\right]^{\frac{1}{2}} = \text{function}\left[(\Delta\theta g h^3/\theta\nu^2),\ (\frac{h}{b})\right] \qquad (2)$$

The first independent dimensionless group is the Grashof Number, Gr, and the second is the aspect ratio, M, of the opening. If the temperature differences are small in comparison with the absolute temperatures, equation (2) may be written in terms of volume flow rate, and θ may be regarded as the mean between the internal and external absolute temperatures. The volume flow rate, Q, is therefore given by,

$$Q = A.\text{function}(Gr,M).\ (\frac{g\Delta\theta h}{\theta})^{\frac{1}{2}} \qquad (3)$$

If the following assumptions are made,

(i) viscous forces are small in comparison with those due to buoyancy, ie Gr is large, and

(ii) the vertical component of velocity at the opening is small in comparison with horizontal components ie the flow consists of two-dimensional horizontal layers,

then, as Shaw (6) and Brown and Solvason (7) have shown,

$$\text{function}(Gr,M) = \frac{1}{3}Cd. \qquad (4)$$

Cd is the discharge coefficient for the opening, which if the latter is sharp-edged will approach the theoretical value of 0.61 at high Grashof numbers. Experimental results by Shaw confirm that this value is appropriate for openings typical of the size of open windows, for a range of $\Delta\theta$ less than 20 deg C.

Multiple Openings

Brown and Solvason (7) have noted that the analysis for a single opening can be extended to deal with openings of various dimensions separated by different vertical distances. The simplest arrangement consists of two openings of areas, A_1 and A_2, with their centres at a height H apart. The flow rate is then given by,

$$Q = \sqrt{2}ACd \left[\frac{\varepsilon}{(1 + \varepsilon)(1 + \varepsilon^2)^{\frac{1}{2}}}\right] \left[\frac{g\Delta\theta H}{\theta}\right]^{\frac{1}{2}} \qquad (6)$$

If the areas are equal, ε equals 1 and equation (6) reduces to,

$$Q = \tfrac{1}{2}ACd \left[\frac{g\Delta\theta H}{\theta}\right]^{\frac{1}{2}} \qquad (7)$$

WIND

The structure of the wind is complex, depending inter alia on the stability of the atmosphere and the roughness of the terrain. In general in the lower atmosphere the wind is turbulent and the mean value of its speed, its turbulence characteristics, and to a certain extent its direction vary with height. The resulting flow when the wind interacts with a bluff body, such as a building, is inevitably highly complex and can only be determined by wind tunnel or full-scale studies. Certain broad characteristics may, however be noted. Air deflected across the windward faces separates at sharp corners creating regions of reversed flow. Downstream a wake is formed. The surface of the building is subject to fluctuating pressures related not only to the turbulence in the wind upstream of the building but to the turbulence created by the building itself. Close to the surface is sealed the density of air within the space will also vary about a mean value, ρ_o. If the process is considered to be adiabatic the rate of change of mass of the air within the space and in consequence the rate at which air is transferred through the opening is given by,

$$G = \frac{V\rho_o}{P_i\gamma} \cdot \frac{dp_i}{dt} \tag{11}$$

where p_i is the pressure within the space. In order to make a simple estimate of the magnitude of the flow rate the following assumptions are made.

i) All of the pressure variation occurs at a single frequency, n. The amplitude of the fluctuating component of the external pressure at the opening, p'_e , is therefore given by,

$$p'_e = \sqrt{2}.\tfrac{1}{2}\rho_o U_T^2.\hat{C}p_e \tag{12}$$

ii) The mass of external air which enters during each cycle mixes perfectly, and hence the outgoing air on the other half of the cycle contains 'contaminated' air from within the space.

iii) That the internal pressure follows the external pressure without any lag or attenuation, ie the effects of inertia are ignored.

The use of these assumptions, together with equation (11) leads to the following expression for an equivalent volume flow rate,

$$Q = \sqrt{2}\left[\frac{\hat{C}p\rho_o}{\gamma p_o}\right].\ nU_T^2V \tag{13}$$

analysis difficult. However the typical window dimension is generally very much smaller than the typical dimension of a building. In consequence the flow in the vicinity of an opening will be parallel to the plane of the wall. Neglecting, initially, the fact that it is turbulent and considering the mean flow at the opening itself, the flow resembles the 'mixing' layer formed when a uniform stream is exposed to a region of zero velocity at one edge. Although it is only a two-dimensional approximation it is suggested that this flow, which is comparatively well understood be used as a first step in the determination of the turbulent exchange of fluid across the opening.

Figure 2 shows the assumed pattern of flow. Outside of the mixing layer the free stream has a uniform velocity equal to the mean velocity at the opening, U_L. At the inner edge of the layer the longitudinal velocity, u, is zero. At the magnitude of Reynolds number based on the opening dimensions the flow will be turbulent within the layer. A number of theoretical solutions based upon the classical phenomenonological theories of turbulence have been derived for the distribution of mean velocity, u, and concentration of any species, c, within the layer, notably by Tollmien (11) and Görtler (12). In general good agreement with experimental results can be obtained with any of these solutions since they each contain at least one arbitrary constant. All are based upon the assumption of similar profiles for velocity and concentration. Thus u and c may be expressed as functions of suitably chosen similarity variable, η, where

$$\frac{u}{U_L} = f_1(\eta) \quad ; \quad \frac{c}{c_i} = f_2(\eta) \text{ and } \eta = \frac{(y - y_i)}{\alpha x}$$

y_i is the value of y at the inner edge of the layer and is a constant which

The value of η_r may be fixed by considering the principle of continuity applied to the enclosed space. If it is completely sealed OB is a mean streamline and there can be no net transfer of fluid across it, and $\eta_r = \eta_{ro}$, say. Thus the flow returning into the space across BC must be equal to the entrained flow along the edge OC, thus,

$$\int_o^b v_i \; dx \quad = \quad \alpha b U_L \int_o^{\eta_{ro}} f_1(\eta) \; d\eta \quad = \quad \alpha b U_L g_2(\eta_{ro}) \qquad (18)$$

where,

$$g_2(\eta_r) \text{ is defined as } \int_o^{\eta_r} f_1(\eta) d\eta$$

Thus,

$$g_2(\eta_{ro}) \quad = \quad \frac{v_i}{\alpha U_L} \quad = \quad (I_1 - I_2)$$

and hence η_{ro} may be determined and the position of the layer fixed.

In order to proceed further it is necessary to propose suitable expressions for the functions $f_1(\eta)$ and $f_2(\eta)$. There is little to choose for this present purpose between the various theoretical solutions and for ease of manipulation the functions proposed by Abramovitch (13) will be used:

$$f_1(\eta) \quad = \quad \left[1 - (1-\eta)^{3/2} \right]^2 \quad ; \quad f_2(\eta) \quad = \quad (1-\eta)$$

The functions $g_1(\eta_r)$ and $g_2(\eta_r)$ and the integrals I_1 and I_2 may now be determined, leading to,

$$\eta_{ro} = 0.62 \quad ; \quad v_i = 0.134 \; \alpha U_L \quad ; \quad g_1(\eta_{ro}) = 0.056.$$

It remains to assign a suitable value fo the constant α. Liepmann and Laufer (14) determined experimentally a value of 0.23 for a uniform steady the effect of a flow parallel to the partition. The flow was created by conventional air-conditioning fans and would be expected to be highly turbulent For high velocities the rate of heat transfer was independent of Grashof No. indicating that it was dependent on the flow only. These results have been employed to deduce values of F_L for the three sizes of openings used. Using the previously determined value for η_{ro} of 0.62, and $g_1(\eta_{ro})$ of 0.056, in conjunction with equation (16) values of α have been determined and are listed with their corresponding values of F_L in Table 1.

TABLE 1 Values of F_L and determined from Brown & Solvason (7)

Opening Dimensions (m)	F_L	α
0.15 x 0.15	0.130	1.84
0.23 x 0.23	0.096	1.71
0.30 x 0.30	0.090	1.60

Single Opening with a Vane

The mechanisms due to wind discussed so far have been applicable to plane openings. A vane will interact with the local airflow creating an exchange of air across the opening. Again the complexi nature of the flow precludes theoretical analysis. Using dimensional analysis the main independent variabl may be identified.

$$F_L = \text{function } (\phi, \beta, M, Re_L).$$

The sense of ϕ and β is indicated in Figure 3.

If we assume that the aspect ratio, M, and the Reynolds number, Re_R will not be important. In the case of the Reynolds number this is effectively reiterating assumptions that have already been made when discussing the separate action of these two mechanisms. Thus,

$$F_R = \text{function } (Ar_R) \qquad (20)$$

When temperature difference is the predominant effect, ie when Ar_R is large the ventilation flow rate will tend to that predicted by equation (5), which on division by U_R gives,

$$F_R = \frac{1}{3}J(\phi)Cd.(Ar_R)^{\frac{1}{2}} \qquad (21)$$

When wind dominates, $Ar_R \to 0$, and F_R becomes independent of Ar_R. This suggests a useful basis of judgement in the analysis of measurements made in full size buildings, where control over the main variables, wind speed, direction and temperature difference is not possible. To isolate those results mainly influenced by wind the results may be plotted in the form F_R against $Ar_R^{\frac{1}{2}}$. Measurements dominated by temperature will tend to lie along the straight line defined by equation (21), whereas those largely due to wind will lie between the F_R axis and the line, equation (21).

WIND TUNNEL STUDIES

Experimental Arrangement

The working section of a small open jet wind-tunnel, described by Sexton (16), was altered so that it was totally enclosed with height 0.8 m and width 1.1 m. A small test chamber was constructed to have one wall in common with the side wall of the wind-tunnel. Its dimensions were 0.5 x 0.5 m in section. The depth away from the tunnel wall could be varied between 0.5 and 1.0 m,