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ON NATURAL VENTILATION OF A BUILDING WITH TWO OPENINGS

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SYNOPIS

Analytical solutions are derived for calculating natural ventilation flow rates in a single-zone building with two openings when no thermal mass is present. In these solutions, the independent variables are the heat source strength and wind speed, rather than given indoor air temperatures. Three air change rate parameters α, β and γ are introduced to characterise respectively the thermal buoyancy force, the conduction heat loss effect, and the wind force. The wind can either assist the buoyancy force or oppose it. For assisting wind the flow is always upwards and the solutions are straightforward. For opposing wind, the flow can be either upwards or downwards depending on the relative strengths of the two forces. In this case the solution for the flow rate as function of the heat source strength presents some complex and unusual features.

LIST OF SYMBOLS

A	area of the envelope
A_b	area of the bottom opening b
A_t	area of the top opening t
A^*	effective opening area
C_d	discharge coefficient
C_p	pressure coefficient
E	total heat power
E_i	heat from people, equipment and lighting
E_s	direct solar gain through windows
g	gravitational acceleration
h	height between two vertical openings t and b
ΔP_w	wind pressure
q	volumetric flow rate
T_i	air temperature in the building
T_o	outdoor air temperature
$T_{solair,j}$	sol-air temperature acting on building element j
V	wind speed
U_j	U-value of building element j

Greek Symbols

α	thermal buoyancy air change parameter
β	fabric loss air change parameter
γ	wind air change parameter
ρ	air density

Subscripts

o	outside
i	inside
b	bottom opening
t	top opening
w	wind

1. INTRODUCTION

Natural forces, in particular thermal buoyancy and wind, drive natural ventilation of buildings. There are a large number of governing factors in natural ventilation, such as wind speed and direction and its turbulence, the size and position of ventilation openings, heat sources, the envelope conductance, and so on. Accurate prediction of natural ventilation rate at the design stage is often very difficult. The key to accurately predicting natural ventilation rates lies in predicting the combined effects of the two natural forces.

In most design problems, the thermal buoyancy force and ventilation flow rates are interdependent. Most studies in the past only considered situations where the indoor air temperatures are given, see Foster and Down (1987) and Andersen (1995). Etheridge and Sandberg (1984) and Etheridge and Stanway (1988) presented two excellent parametric investigations. Their studies used a non-dimensional approach to demonstrate the relative importance of the various parameters. However, they assumed that the indoor air temperatures are known. In reality, the heat sources, wind speed and thermal conductance of the building envelope are known, and the indoor air temperature and ventilation flow rate are derived from these parameters.

Although numerical methods can now be used to revisit the work of Etheridge and Sandberg (1984) and Etheridge and Stanway (1988), and produce non-dimensional graphs for the simple cases they considered, an analytical method is preferred before a full numerical study is carried out. It is much easier to carry out a parametric study with analytical solutions than with numerical experiments.

Most today's design codes on natural ventilation still adopt simple semi-analytical solutions (i.e. the hot air column model and cross-wind ventilation model) as design tools, such as those in the CIBSE design guide (CIBSE, 1988) and BS5925 (1991). These formulae have been shown to provide reasonable estimates of natural ventilation flow rates in many situations. However, one of the difficulties in using them is that the indoor air temperature must be known beforehand. One has to adjust the air temperature used after the natural ventilation flow rate has been calculated. To obtain a consistent estimate of both flow rate and indoor air temperature is quite often practically not possible.

This paper derives analytical solutions for the ventilation rate in a single-zone building with two openings, considering the effect of buoyancy force, wind force and heat conduction loss through the building envelope, and their interactions. We assume that there is no thermal mass in the building. If thermal mass is included, no analytical solution exists. However, the model can still apply to some practical buildings such agricultural (e.g. livestock) and industrial buildings with relatively low thermal mass. When ventilation air flow rates are very large, then the thermal mass may also be neglected. The effect of thermal mass on natural ventilation will be a subject of a future paper.

2. NATURAL VENTILATION DRIVEN BY COMBINED THERMAL AND WIND FORCES

Consider a simple building with two openings at different vertical levels on opposite walls, as shown in Figure 1. There is an indoor source of heat, E_i, and solar radiation acts on the building via a sol-air temperature for the opaque elements and solar heat gain through windows. The wind force can assist or oppose the thermal buoyancy force. We assume that the indoor air is fully mixed, i.e. the air temperature is uniform. This assumption is generally not valid for thermal buoyancy force-dominated flows. Wind turbulence effects are not included.

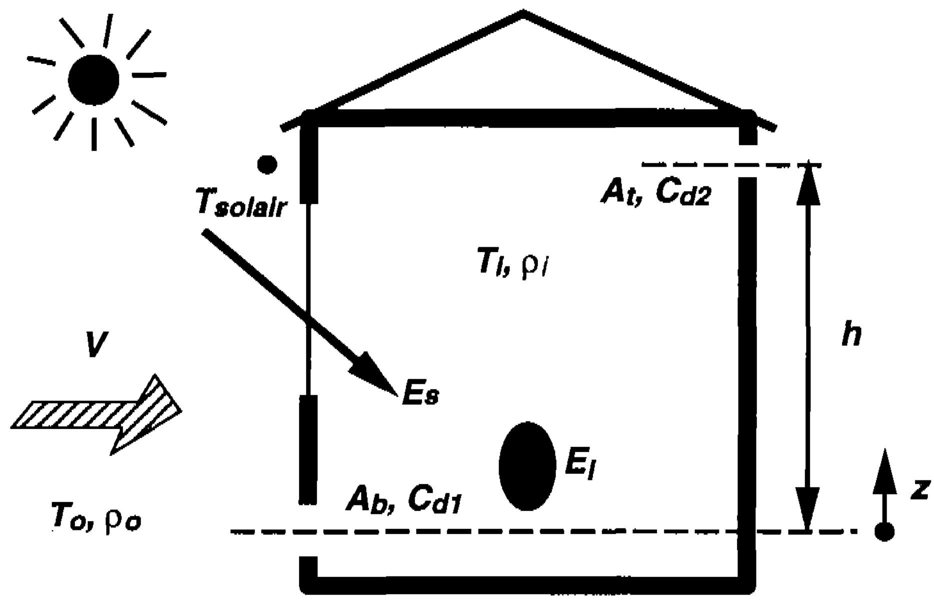

Figure 1. A two-opening building with solar radiation through windows

A heat balance on the building gives

$$\rho c_p q(T_i - T_o) + \sum_j U_j A_j (T_i - T_{sol-air,j}) = E_i + E_s . \tag{1}$$

This can be rearranged as

$$\rho c_p q(T_i - T_o) + \sum_j U_j A_j (T_i - T_o) = E \tag{2}$$

where

$$E = E_i + E_s + \sum_j U_j A_j (T_{solair,j} - T_o). \tag{3}$$

Depending on the arrangement of ventilation openings, wind can assist or oppose the thermal force in natural ventilation. Two extreme situations are considered here, i.e. fully assisting and fully opposing. These occur when there are only two ventilation openings. It appears that no analytical solutions exist for more than two openings.

2.1 Assisting Wind Force

It is easy to show that the flow rate is given by

$$q = C_d A^* \sqrt{2gh \frac{T_i - T_o}{T_o} + 2\Delta P_w} \ , \tag{4}$$

where the effective opening area, A^*

$$A^* = \frac{A_t A_b}{A_t^2 + A_b^2} \ , \tag{5}$$

and the wind pressure, ΔP_w

$$\Delta P_w = \frac{1}{2} C_{p1} V_1^2 - \frac{1}{2} C_{p2} V_2^2 \ , \tag{6}$$

where the subscripts 1 and 2 refers to two ventilation openings. ΔP_w is always non-negative. In equation (4) the C_d values are assumed to be the same for both openings. It is fairly easy to derive the formula for non-equal C_d values. Both A_b and A_t are free-opening areas. In deriving equation (4), the power-law equation was used to describe the relationship between the flow rate and the pressure difference.

Substituting equation (2) into (4) gives, after some manipulation,

$$q^3 + 3\beta q^2 - 3\gamma^2 q - 2\alpha^3 - 9\gamma^2 \beta = 0 \tag{7}$$

where

$$\alpha = \left(C_d A^*\right)^{\frac{2}{3}} \left(\frac{Egh}{\rho c_p T_o}\right)^{\frac{1}{3}} , \tag{8}$$

$$\beta = \frac{\sum_j U_j A_j}{3\rho C_p} \tag{9}$$

and

$$\gamma = \frac{1}{\sqrt{3}} \left(C_d A^*\right) \sqrt{2\Delta P_w} \ . \tag{10}$$

The three air change parameters α, β and γ quantify respectively the effects of heat gains, fabric heat losses, and wind. For a perfectly insulated building, when the buoyancy force acts alone, $q = \sqrt[3]{2}\alpha$, and when the wind force acts alone, $q = \sqrt{3}\gamma$.

There are many graphical ways to present the ventilation flow rate as a function of these parameters. Examination of equation (7) shows that the solution can be easily presented in a non-dimensional graph, shown in Figure 2. The important non-dimensional ratio α/γ is a relative measure of the two driving forces.

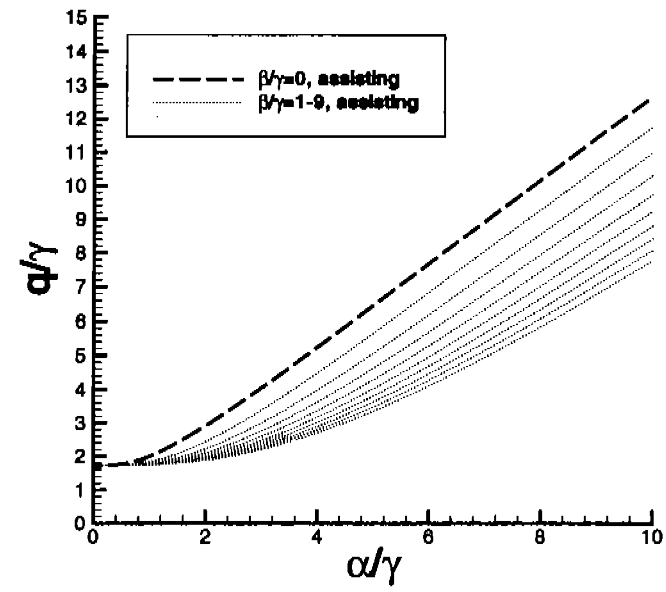

Figure 2. Natural ventilation graph for combined forces with assisting winds – non-dimensional flowrate vs heat gain parameter at varying insulation levels.

The effect of heat loss on ventilation flow rate is not linear. There is a big drop in the ventilation flow rate as β increases from 0. As β further increases, the resulting rate reduction in the ventilation flow rate slows down.

Figure 2 is not applicable when $\gamma = 0$, i.e. no wind. A much simpler graph can be produced (not shown here). For design purposes, Figure 2 is easy to use. A similar graph can be produced for indoor air temperature. Air temperatures can also be calculated by equation (4).

2.2 Opposing Wind Force

So far the flow direction considered is always upward. When the wind force opposes the thermal buoyancy force, i.e. the wind blows onto the upper opening, the flow can be either upward or downward, depending on the relative strength of the forces. Again, it can be shown that

$$q = C_d A^* \sqrt{\left| 2gh\frac{T_i - T_o}{T_o} - 2\Delta P_w \right|}\,. \qquad (11)$$

Applying the heat balance equation gives

$$q^3 + 3\beta q^2 = \left|2\alpha^3 - 3\gamma^2 q - 9\gamma^2 \beta\right|. \tag{12}$$

For upward flows, the buoyancy force is stronger and $2\alpha^3 > 3\gamma^2 q + 9\gamma^2 \beta$. We have

$$q^3 + 3\beta q^2 + 3\gamma^2 q - 2\alpha^3 + 9\gamma^2 \beta = 0. \tag{13}$$

For downward flows, the wind force is stronger and $2\alpha^3 < 3\gamma^2 q + 9\gamma^2 \beta$. We have

$$q^3 + 3\beta q^2 - 3\gamma^2 q + 2\alpha^3 - 9\gamma^2 \beta = 0. \tag{14}$$

Analytical solutions of equations (13) and (14) can be written down, but in practice they are best solved numerically. However, an analysis of the behaviour of the flow rate as a function of α (the heat source) reveals that the general form of the solution must be as shown in Fig. 3.

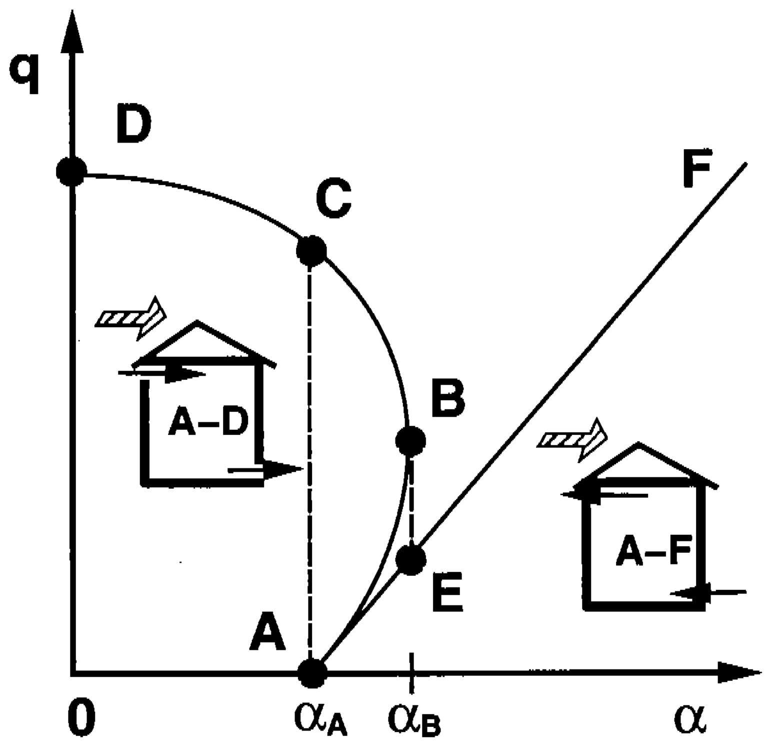

Figure 3. A sketch of the analytical solutions of equation (12)

This shows some interesting features. For example, consider a very low value of α, so that the flow is definitely downward. As α increases, we move to the right along the downward flow curve, and the flow rate decreases. However, when α reaches a critical value, α_B, denoted by point B in Fig. 3, an interesting phenomenon occurs. If α increases slightly, the flow direction reverses to upward flow and the flow rate drops to a lower value, denoted by point E. If α then increases further the flow rate increases, as would be expected. However, if at E α now decreases, the upward flow rate can decrease to zero at $\alpha = \alpha_A$, at point A. If α further decreases, then the flow reverses to downward, and the ventilation flow rate jumps to point C.

Furthermore, for $\alpha_A < \alpha < \alpha_B$, there appear to be three possible flow rates for a given value of α: two downward flows and one upward flow.

Finally, the state of the system represented by the curve A-B is unusual. Here the flow direction is downward, but an increase in α results in an increase in the flow rate. This is counter-intuitive: because the wind is opposing the buoyancy force and is stronger (i.e. downward flow), one would expect that an increase in the buoyancy force would result in a decrease in the flow rate, not an increase. Thus the curve A-B may a non-physical region, even though points on this curve do satisfy the original equations. It is not clear what other constraint can be applied to show that A-B is non-physical.

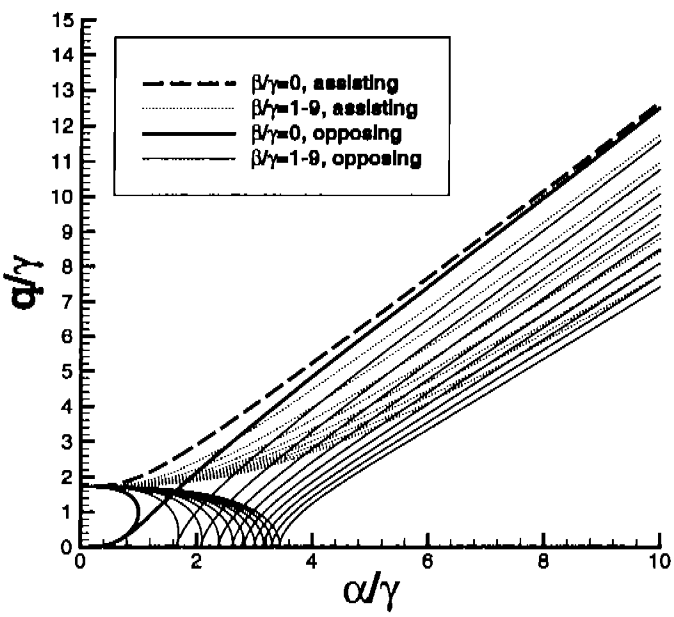

Figure 4. Non-dimensional flowrate vs heat gain parameter at varying insulation levels for both assisting and opposing winds.

3. CONCLUSIONS

Analytical solutions are derived for natural ventilation in a single-zone building with two openings. Three air change parameters are introduced: the thermal buoyancy air change parameter α, the wind air change parameter γ and the fabric loss air change parameter β. We believe that simple ventilation graphs, such as Figures 2 and 4, can be used for design purposes. By analysing these graphs and the underlying equations, the following conclusions can be drawn.

- The ventilation flow rate is simply proportional to α or γ, when each driving force acts alone.
- The effect of heat loss through the building envelope is very significant. The ventilation flow rate drops sharply as β increases from 0. The rate of change in the ventilation flow rate slows down when β further increases. When a wind force is present, the heat loss effect also interacts with wind-induced flows. This is due to the fact that heat loss depends on indoor air temperature, which is again controlled by the ventilation flow rate.
- When the wind force opposes the thermal buoyancy, for a certain range of α values, there appears to be three possible flow rates for a given value of α: two downward flows and one upward flow, depending on whether α has been increasing or decreasing, i.e. the system exhibits hysteresis.
- With an opposing wind force, for a given set of α and γ values it is possible that two different β values can result in the same ventilation flow rate, but in opposite flow directions.

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