HOW DO WINDS AFFECT BUOYANCY-DRIVEN VENTILATION IN BUILDINGS?

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ABSTRACT This paper examines theoretically the effects of wind on buoyancy-driven ventilation via some new analytical solutions recently developed by the authors. Three air change rate parameters are introduced to characterise respectively the effects of thermal buoyancy, the envelope heat loss and the wind force. The wind can either assist or oppose the airflow. For the first time, it has been found that for opposing winds, there are two stable ventilation flow rates for a given set of wind and thermal parameter, i.e. the natural ventilation flow exhibits hysteresis.
Simple non-dimensional graphs are presented for calculating ventilation flow rates, and for sizing ventilation openings. Using the simple examples, this paper provides architects and engineers with some practical guidelines on how to use these non-dimensional graphs in their concept design.

1 Introduction

Natural ventilation has been an attractive method for ventilation and passive cooling in low energy buildings. Wind is one of the two causes of airflow through a naturally ventilated building; thermal buoyancy is the other, which is due to the differences in density between inside and outside air. For a simple building with only two openings, it is a simple matter to calculate the ventilation flow rates, q_w or q_s, driven by each of the two natural forces. When the two forces act at the same time, it is often suggested the combined ventilation flow rate can be calculated as $\sqrt{q_s^2 + q_w^2}$. This implies that winds always assist buoyancy-driven ventilation in buildings.

Is this true? By seeking answers to this question, we would like to demonstrate how the simple natural ventilation problem can result in very complex dynamic phenomena. The answer to the question affects how the combined ventilation flow rate should be calculated, how to avoid undesirable designs and how to size ventilation openings.

2 A simple building and some well-known formulae

Consider a simple building with two openings at different vertical levels on opposite walls, as shown in Fig.1. The heights of the two openings are relatively small compared to the building height. 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, but improves as the wind strengthens.

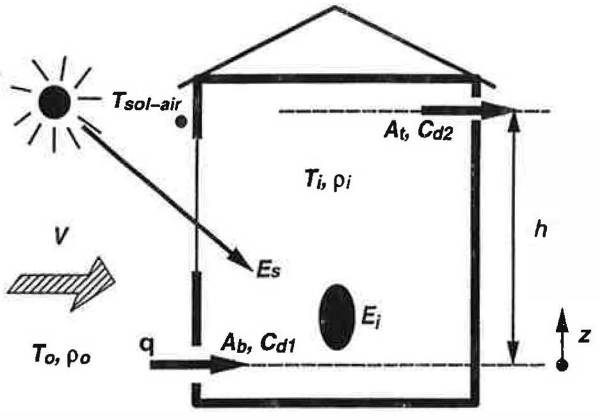

Fig.1 A simple two-opening building showing the notation used in the text

Let us first define the effective area A^* and the wind pressure ΔP_w:

$$A^* = \frac{A_t A_b}{\sqrt{A_t^2 + A_b^2}} \tag{1}$$

$$\Delta P_w = \frac{1}{2}\rho_o C_{p1}^2 V^2 + \frac{1}{2}\rho_o C_{p2}^2 V^2 \tag{2}$$

where ρ_o = density of outdoor air, C_{p1} and C_{p2} are wind pressure coefficients
Assuming equal C_d values for simplicity, the ventilation flow rate due to wind alone can be calculated as follows:

$$q_w = C_d A^* \sqrt{\frac{2\Delta P_w}{\rho_o}} \tag{3}$$

The ventilation flow rate due to buoyancy alone can be calculated as follows:

$$q_w = C_d A^* \sqrt{2gh\frac{T_i - T_o}{\rho_o}} \tag{4}$$

where g is gravity. The ventilation flow rate due to combined wind and buoyancy forces can be calculated either by the conventional formula

$$q = \sqrt{q_w^2 + q_s^2} \tag{5}$$

or by

$$q = C_d A^* \sqrt{\left| 2gh\frac{T_i - T_o}{T_o} \pm 2\frac{\Delta P_w}{\rho_o} \right|} \tag{6}$$

It should be noted that equations (5) and (6) are not identical. In equation (6), if the wind assists the flow, then the two pressures add together. It can be easily shown that equation (5) and (6) are identical in this situation (however this conclusion may not hold for more complex situations, say more than two openings). When wind opposes the flow, two situations are possible, i.e. the buoyancy force is stronger or the wind force is stronger.

Thus by examining equation (6), one can obtain the following conclusions, see (Etheridge and Sandberg 1984):

- When the wind assists the flow, the quadratic formula (5) can be applied to calculate the combined ventilation flow rate.
- When the wind opposes the flow, there are two situations, i.e. downward flows and upward flows, and the quadratic formula (5) is no longer valid.
- One should always try to avoid designs with opposing wind situations, as opposing winds reduce the ventilation rate.

3 New solutions

When natural ventilation is induced by thermal buoyancy forces, the flow rates and indoor air temperatures are interdependent. Wind forces can either assist or oppose the thermal buoyancy force. Li and Delsante (1999) recently suggested a simple analytical solution for the ventilation flow rate and indoor air temperature in a single-zone building. Because of the non-linearity of the flow rate balance equation, analytical solutions only exist when there are two effective ventilation openings. Three air change rate parameters α, β and γ are introduced to characterise respectively the effects of the thermal buoyancy force, the envelope heat loss and the wind force.

Thermal buoyancy: $\alpha = (C_d A^{*})^{\frac{2}{3}}(Bh)^{\frac{1}{3}}$ (7)

Envelope heat loss: $\beta = \dfrac{\sum U_j A_j}{3\rho c_p}$ (8)

Wind: $\gamma = \dfrac{1}{\sqrt{3}}(C_d A^{*})\sqrt{2\Delta P_w}$ (9)

where $B = (Eg/\rho_o c_p T_o)$, the buoyancy flux, c_p = *heat capacity of air*. U_j and A_j are the *U*-values and area of wall element *j* respectively. For assisting winds, the ventilation flow rate, *q*, is determined by the following equation:

$$q^3 + 3\beta q^2 - 3\gamma^2 q - 2\alpha^3 - 9\gamma^2\beta = 0 \quad (10)$$

For opposing winds, the flow rate is determined by the following equation:

$$q^3 + 3\beta q^2 = |-3\gamma^2 q + 2\alpha^3 - 9\gamma^2\beta| \quad (11)$$

The detailed derivation of the above equations can be found in Li and Delsante (1999).

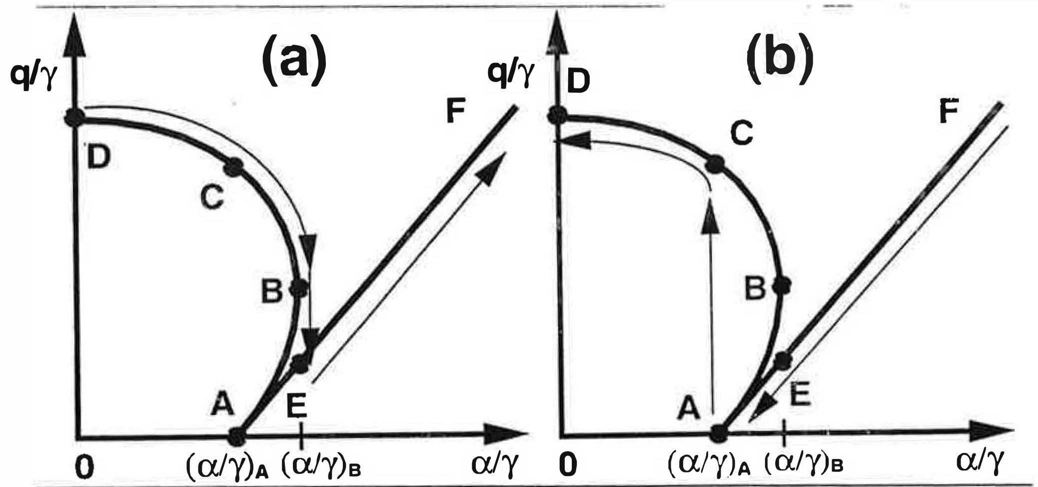

Fig.2 Analytical sketch of the opposing wind situations

The solution of the opposing wind situations is very complex and it needs some explanation. The behaviour of the flow rate as a function of α and γ reveals that for β ≠ 0 the general form of the solutions must be as shown in Fig.2.

This solution is very interesting. It can be shown that a solution on the A-B curve is not stable, see Li and Delsante (1999). The flow exhibits hysteresis. We consider two situations, i.e. α/γ increasing or decreasing. For a constant α, one can increase α/γ by reducing the wind speed.

- In Fig.2a, α/γ increases from a very low value at point D. The flow is initially downward. As α/γ increases, we move to the right along the downward flow curve, and the flow rate decreases. At a critical value, $(\alpha/\gamma)_B$, denoted by point B in Fig.2a, if α/γ increases slightly, the flow direction reverses to upward flow and the flow rate drops to a lower value, denoted by point E. If α/γ then increases further, the flow rate increases, as would be expected.

- When α/γ decreases from a very high value, say point F in Fig.2b, the flow is initially upward. The upward flow rate can decrease to zero at $\alpha/\gamma = (\alpha/\gamma)_A$, at point A. If α/γ further decreases, then the flow reverses to downward, and the ventilation flow rate jumps to point C.

We define two turning points in the flow system, $(\alpha/\gamma)_A$ and $(\alpha/\gamma)_B$, which will be referred to as the "A turning point" and the "B turning point". At a turning point, the flow direction reverses. The A turning point is a downward-flow turning point: the flow reverses from upward to downward flow; the B turning point is a upward-flow turning point: the flow reverses from downward to upward flow.

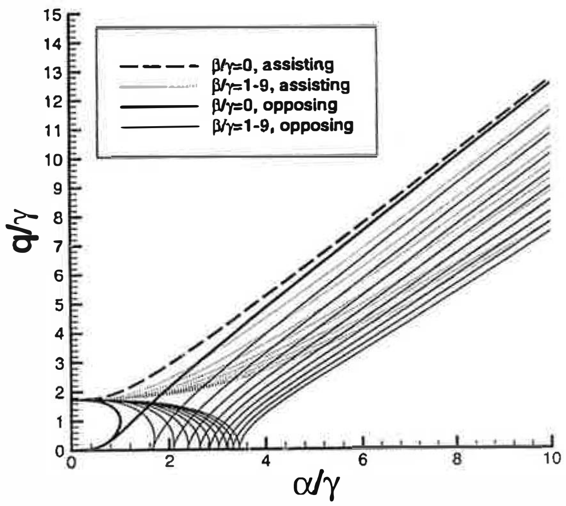

Fig.3 Ventilation flow rates for combined forces - both opposing and assisting winds.

A non-dimensional graph of the flow rate is presented in Fig.3. This graph is not applicable when there is no wind. For assisting winds, at $\alpha/\gamma = 0$, the ratio q_v/γ is $\sqrt{3}$. There is also a strong reduction effect as the envelope heat loss parameter β increases.

When the building is perfectly insulated, the B turning point always occurs when $\alpha = \gamma$, i.e. when the two driving forces are balanced. The A turning point always occurs when the buoyancy force does not exist or the wind force is infinite. The two turning points converge when β/γ is very large.

The turning points also represent the minimum upward ventilation rates that the system can achieve for a given β. In theory, the upward ventilation flow rate at the A turning point, q_A, is always zero. However, the upward ventilation flow rate at the B turning point, q_B, approaches zero as β increases.

An example of the three theoretical solutions that exist between the two turning points is given in Fig.4. The solutions are for a perfectly-insulated building, i.e. $\beta = 0$, and with $\alpha = 0.9$, $\gamma = 1$. All three solutions satisfy both the heat balance equation and the simplified momentum equation. While the downward flow of 1.40 m^3/s and the upward flow of $0.45m^3/s$ are stable, the downward flow of $0.54m^3/s$ (on the A-B curve in Fig.2) is not stable, as shown by Li and Delsante (1999).

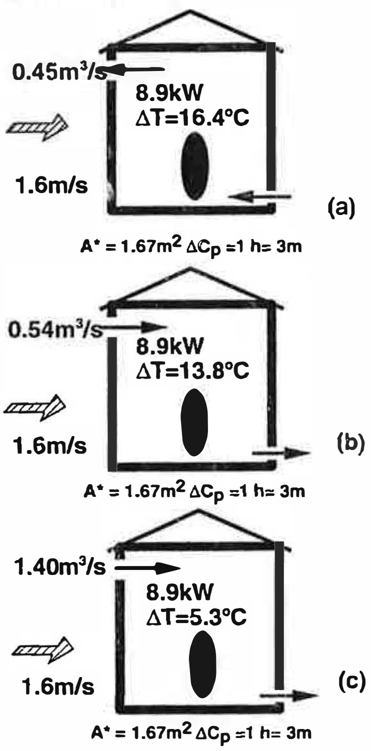

Fig.4 Three possible flow states in a building with the same ventilation parameters

4 Design considerations

For design purposes, Fig.3 is simple to use. In this paper, we distinguish three different design problems:

- Geometry-based design - For a building with known ventilation openings and specified wind conditions, the air temperature needs to be determined.
- Thermal comfort-based design - For a building with a targeted indoor air temperature, the ventilation openings and the airflow rate need to be determined.
- Indoor air quality-based design - For a building with a targeted airflow rate, the ventilation openings and the indoor air temperature need to be determined.

Fig.3 is only applicable for buildings with negligible thermal mass and two effective ventilation openings. A procedure for applying Fig.3 to the above three design problems is suggested as follows, for assisting wind situations:

- Geometry-based design - From the heat source strength and the ventilation opening areas, one determines α. From the *U*-values and heat transfer areas, β can be calculated. The wind parameter γ can be calculated from the ventilation openings and the wind pressure. Fig.3 can then be used to find the ventilation flow rate. The air temperature can be calculated using equation (6).

- Thermal comfort-based design - From a simple heat balance equation (not given here), one can determine the required ventilation flow rate as the indoor air temperature is known. Calculate the wind pressure, ΔP_w and use the flow rate equation (6) to determine the effective ventilation area. If one opening area is known, then the required size of the second opening can be determined easily. Calculate α, β and γ to check the system performance in Fig.3 to see the balance of the natural ventilation forces.
- Indoor air quality-based design - From a simple heat balance equation (not given here), one can determine the indoor air temperature as the required ventilation flow rate is known. Calculate the wind pressure, ΔP_w, and use the flow rate equation (6) to determine the effective ventilation area. If one opening area is known, the second one can be determined easily. Calculate α, β and γ to check the system performance in Fig.3 to see the balance of the natural ventilation forces.

The opposing wind design configurations should be avoided in buildings if possible, by placing the lower opening to face the prevailing wind direction. However, if such a design cannot be avoided in practice, the impact of opposing winds needs to be considered, as the results can be very misleading if the quadratic formula (5) used.

Considering the example given in Fig.4, there are two stable solutions according to our new analytical method.

- Solution (a): If one maintains a temperature difference of 16.4°C, the buoyancy alone will generate a flow rate of 1.80 m^3/s. The wind force alone drives a flow rate of 1.73 m^3/s. According to the quadratic formula (5), the flow rate should be 2.50 m^3/s. It is clear that this overestimates the ventilation flow rate. The flow rate is only 0.45 m^3/s according to our new solution (Fig.3).
- Solution (c): If one maintains a temperature difference of 5.3°C, the buoyancy alone will generate a flow rate of 1.00 m^3/s. The wind force alone again drives a flow rate of 1.73 m^3/s. According to the quadratic formula (5), the flow rate should be 2.00 m^3/s. The flow rate is 1.40 m^3/s according to Fig.3.

5 Conclusions

The effects of winds on buoyancy-driven ventilation in a simple building can be analysed using three air change parameters: α, β and γ. When the wind force opposes the thermal buoyancy, then for a certain range of α/γ values there appear to be two stable flow rates for a given value of α/γ: one downward flow and one upward flow. The opposing wind design configurations should be avoided in buildings if possible.

6 Acknowledgment

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7 References

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