PREDICTING NATURAL VENTILATION IN A TWO-ZONE BUILDING DRIVEN BY COMBINED FORCES

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ABSTRACT

Natural ventilation relies on less controllable natural forces so that it needs more artificial control, and thus its prediction, design and analysis become more important. This paper presents both theoretical and numerical simulations for predicting the natural ventilation flow in a two-zone building with multiple openings which is subjected to the combined natural forces. To our knowledge, this is the first analytical solutions obtained so far for a building with more than one zones and in each zone with possibly more than 2 openings. The analytical solution offers a possibility for validating a multi-zone airflow program. A computer program MIX is employed to conduct the numerical simulation. Good agreement is achieved. Different airflow modes are identified and some design recommendations are also provided.

KEYWORDS

Natural ventilation, Two-zone building, Large openings

INTRODUCTION

Natural ventilation has received increasing attention in architectural design over recent years due to increasing worldwide recognition of the sustainable building concept. Natural ventilation relies on the natural forces, i.e. buoyancy, wind or combined forces to drive the air to circulate in the buildings through openings without extra energy input, thus it is regarded to be one of the environment-friendly building technologies and play a significant part in achieving the so-called green building design.

It is important to predict natural ventilation performance including possible airflow rate and/or airflow paths before and during both conceptual and detailed design stages. High airflow rate can ensure good indoor air quality and cooling capacity when the temperature of outdoor air is relatively low. The preferred airflow path is highly appreciated for smoke and infection control. Compared with mechanical ventilation, natural ventilation is more difficult to predict on account of its more dependence on the variable and uncertain natural driving forces. An analytical solution is probably the best way for evaluating the computer algorithms of an airflow program. However, due to the highly non-linear characteristics in natural ventilation flow network, analytical solutions can only be obtained in limited situations, although they offer a better way of checking the accuracy of a numerical method. Theoretical analysis for the natural ventilation in a single-zone building with two or multiple openings considering single or combined driving forces is extensively investigated by the researchers (Linden et al 1990, Li and Delsante 2000, and Chen and Li 2002). It shows that airflow rate depends on various parameters, e.g. building geometry, heat source, opening size and relative height, and wind can be either against or assisting buoyancy which brings about different airflow patterns. Moreover, the theoretical analysis was also conducted in interconnected two zones by Lin and Linden (2002), Holford and Hunt (2003), Flynn and Caulfifld (2006), and Ji and Cook (2007). Particularly, as shown in Yang et al. (2006), the non-linear and solution multiplicity of airflow in a two-zone naturally ventilated building were very important. But all these studies were restricted to buoyancy force. Our work in this paper will extend the case in Yang et al (2006) to combined forces with an airflow program where indoor air temperatures are prescribed. To our knowledge, this is the first analytical solution obtained so far for a building with more than one zone and in each zone with possibly more than 2 openings. The results provide some insight into the natural ventilation design for two-zone buildings.

On the other hand, numerical solutions play a significant role in natural ventilation prediction especially in multi-zone airflow network cases. During the past 20 years, there were a large number of multi-zone models available. Feustel and Dieris (1992) identified 50 different models developed between 1970 and 1992. However, most of them focused on crack infiltration rather than natural ventilation through large openings, while this is essential for most practical natural ventilation studies (Li and Heiselberg, 2003). In this paper, a computer program MIX specially developed for predicting natural ventilation in multi-zone buildings is used. The numerical results are compared with the analytical solutions, and a good agreement is achieved.

FUNDAMENTALS OF MIX

MIX was firstly developed in 1990 dealing with infiltration since then. In 2000, MIX program was revised for natural ventilation analysis of multi-zone buildings with multiple large openings and applied to practical problems (Li et al., 2000 and 2005). In MIX, a pressure-based multi-zone formulation combined with an auxiliary concept of external pressure is implemented to predict the airflow rate through the openings of multi-zone buildings. This formulation includes the combined effect of wind, thermal buoyancy and mechanical ventilation, and it can be used for both external and internal large openings.

It is beyond the scope of this paper to discuss the whole theory of MIX program but we will focus on some key concepts. Interested readers can refer to Li et al (2000) for detailed information. It is known that for a single zone with external openings, the total pressure difference by considering combined forces across the opening at a height z can be written as:

$$\Delta p_{tot}(z) = 0.5\rho_0 C_p(z)v^2 - (\rho_0 - \rho_1)g(z - H_1) - p_1 \tag{1}$$

For a single zone building, the building is Zone 1 and outdoors is Zone 0. H_1 is the middle height of Zone1 and the datum level is also at H_1 by default. The term p_1 is defined as the internal zonal pressure, at the datum level relative to the ambient pressure at the same level. For convenience, we also define an effective 'external' pressure, as opposed to the definition of internal pressure p_1,

$$p_{ext}(z) = 0.5\rho_0 C_p(z)v^2 - (\rho_0 - \rho_1)g(z - H_1) \tag{2}$$

Thus

$$\Delta p_{tot}(z) = p_{ext}(z) - p_1 \tag{3}$$

The neutral level can be calculated as

$$z^* = \frac{p_{ext}(0) - p_1}{(\rho_0 - \rho_1)g} \tag{4}$$

Then an alternation for the expression of the total pressure difference can be obtained

when $0 < z < z^*$

$$\Delta p_{tot}(z) = (p_{ext}(0) - p_1)(1 - \frac{z}{z^*}) \tag{5}$$

when $z^* < z < R_1$ (R_1 is the height of the Zone1)

$$\Delta p_{tot}(z) = (p_{ext}(R_1) - p_1)(\frac{z - z^*}{R_1 - z^*}) \tag{6}$$

Basically, the above formulation can be easily extended to multi-zone openings. Internal pressure can be defined in each zone and the total pressure difference across each opening can be also expressed in the form of Eq. (3) but with different expressions of external pressure. MIX considers all the possible situations for the interaction of two zones, i.e. vertically interconnected, horizontally interconnected with same height, horizontally interconnected with different heights, and horizontally interconnected with partially overlapped heights. The detailed calculation of external pressure for various conditions is well explained in Li et al (2000) which will not be repeated here due to the limited length of paper.

We consider that a multi-zone building is composed of N zones, and there are N_i openings for zone i. In the Zone i, the continuity equation is as follows when neglecting the volume compressibility and the differences in density between zones are sufficiently small.

$$\sum_{j=1}^{N_i} q_{j,i} + q_{s,i} + q_{e,i} = 0 \tag{7}$$

Where $q_{j,i}$ is the air flow rate through opening j in zone i and $q_{s,i}$ and $q_{e,i}$ are supply input and exhaust output by mechanical system, respectively. The airflow is always positive if it is inflow, or vice versa. $q_{j,i}$ can be calculated as follows:

$$q_{j,i} = K_t A(|\Delta p_{tot}|)^n \operatorname{sgn}(\Delta p_{tot}) \tag{8}$$

where K_t is the flow coefficient determined by the permeability, shape and size of the opening and A is the area of the opening. For simplicity, n is taken as 0.6 for small openings and 0.5 for large openings. For the large openings, $K_t = C_d\sqrt{2/\rho}$.

The balance of volume flows in all rooms together can be expressed by the following non-linear system of equations:

$$f_i(p_1, p_2 \cdots p_N) = \sum_{j=1}^{N_i} q_{j,i} = 0, \quad i=1,2,\ldots,N \tag{9}$$

This set of non-linear equations can be solved iteratively by Newton-Raphson method together with the Gauss-Jordan elimination.

NATURAL VENTILATION IN A TWO-ZONE BUILDING

A two-zone building with four equal openings is selected as a case study. All walls are assumed to be adiabatic. The temperatures in both zones are considered to be t_1=40°C and t_2=20 °C , respectively. And the ambient temperature t_0=0 °C. Let H_1 be the height between opening 1and opening 3 and H_2 be the height between opening 2 and opening 4. Zone 1 is 2.5 m long, 2 m wide, and 3 m high, and each opening is 0.1 m high and 2 m wide. Wind approaches from two directions as shown in Fig.1 and Fig.2. We are intended to investigate the natural ventilation performance in the two-zone building subjected to combined natural forces through theoretical and numerical simulations.

When wind is approaching from right to left (Fig.1)

Due to the actions of wind assisting or opposing the buoyancy force, there are 4 possible airflow modes, see Fig.3. We will try to illustrate under what conditions those ventilation modes would occur in the following section.

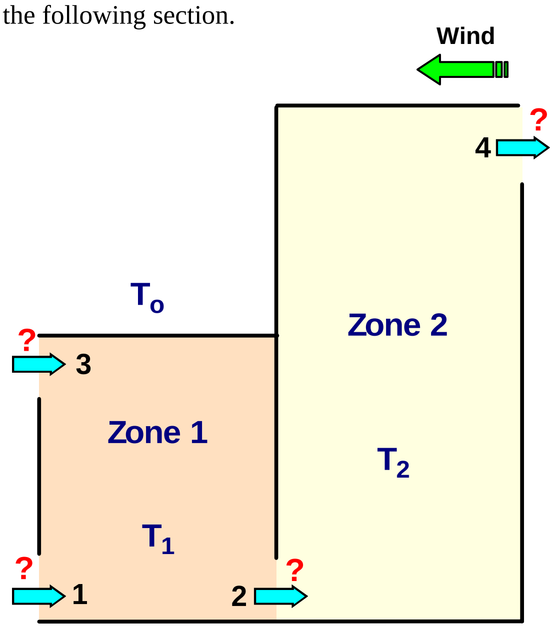


Figure 1 Geometry of a two-zone building with four openings under combined forces (Wind is from right to left)

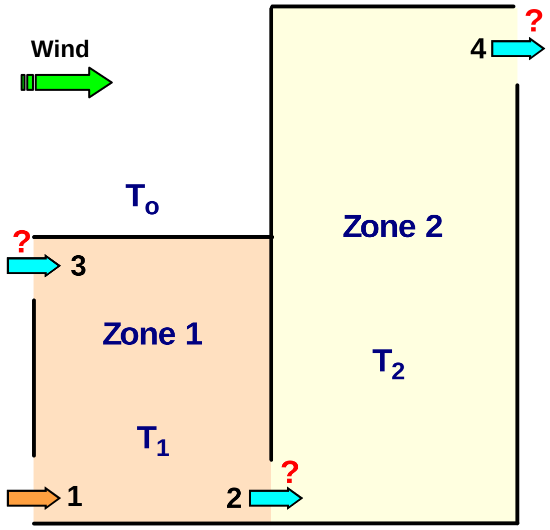
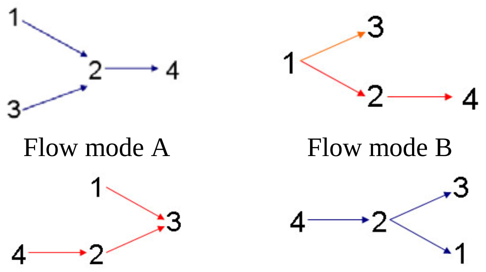


Figure 2 Geometry of a two-zone building with four openings under combined forces (Wind is from left to right)



Flow mode A
Flow mode B
Flow mode C
Flow mode D

Figure3 Different airflow modes when wind is approaching from right to left

- Flow mode A

Air enters Zone 1 through opening 1 and 3, and is discharged outside from opening 4. As we have two zones and four openings, two independent pressure loops can be formed. The governing equations can be written as follows:

$$\begin{cases} \Delta p_1 + \Delta p_2 + \Delta p_4 + \Delta p_w = \rho \dfrac{T_2 - T_0}{T_0} g H_2 \\ \Delta p_1 - \Delta p_3 = \rho \dfrac{T_1 - T_0}{T_0} g H_1 \\ q_1 + q_3 = q_2 = q_4 \end{cases} \tag{10}$$

Where

$$\Delta p_w = \frac{\rho}{2}(C_{p1} - C_{p4}) v^2$$

Let

$$q_b^2 = \frac{2C_d^2 A^2 (T_1 - T_0)}{T_0} g H_1 , \; q_w^2 = \frac{2C_d^2 A^2 \Delta p_w}{\rho} \text{ and}$$

$$F_r = \frac{q_w}{q_b} = \frac{2\Delta C_p T_o v^2}{g H_1 (T_1 - T_o)}$$

F_r indicates the relative strength of the wind and buoyancy forces. Then, an airflow rate can be normalized by q_b and denoted as: $Q_i = \dfrac{q_i}{q_b}$

Therefore, we can obtain:

$$\begin{cases} Q_1^2 + 2Q_2^2 = \kappa \\ 2Q_1 Q_2 - Q_2^2 = 1 \end{cases} \tag{11}$$

Where

$$\kappa = \alpha - F_r^2 , \; \alpha = \frac{T_2 - T_0}{T_1 - T_0} \chi , \; \chi = \frac{H_2}{H_1}$$

There are two roots for this equation:

$$Q' = \begin{cases} Q_1 = \sqrt{\dfrac{5\kappa + 2 + 4\sqrt{(\kappa - 2)(\kappa + 1)}}{9}} \\ Q_2 = \dfrac{\kappa + 2}{4Q_1} - \dfrac{Q_1}{4} \end{cases}$$

and

$$Q^* = \begin{cases} Q_1 = \sqrt{\dfrac{5\kappa + 2 - 4\sqrt{(\kappa-2)(\kappa+1)}}{9}} \\ Q_2 = \dfrac{\kappa+2}{4Q_1} - \dfrac{Q_1}{4} \end{cases}$$

Based on some analysis, we find that only Q^* is the solution to this case, and also κ should satisfy $\kappa \geq 3$. Specially, when $\kappa = 3$, Q_3 =0 which indicates no airflow will go through the opening 3.

- Flow Mode B

Air enters Zone 1 and Zone 2 and flows outside through opening 4 and 3. Similarly, we can obtain the following governing equation:

$$\begin{cases} Q_1^2 + 2Q_2^2 = \kappa \\ 2Q_1^2 - 2Q_1Q_2 + Q_2^2 = 1 \end{cases} \qquad (12)$$

We can get the true root for Eq.(14)

$$Q^* = \begin{cases} Q_1 = \sqrt{\dfrac{\kappa + 6 + 4\sqrt{-\kappa^2 + 5\kappa - 2}}{17}} \\ Q_2 = \dfrac{\kappa-2}{4Q_1} + \dfrac{3Q_1}{4} \\ Q_3 = Q_1 - Q_2 \end{cases}$$

Where $0.5 \leq \kappa < 3$

- Flow Mode C:

The airflow through opening 2 is from Zone 2 to Zone 1 and air flows into the building through opening 1 and 4 and outside through 3.

Similarly, we can obtain the following governing equation:

$$\begin{cases} Q_1^2 - 2Q_2^2 = \kappa \\ 2Q_1^2 + 2Q_1Q_2 + Q_2^2 = 1 \end{cases} \qquad (13)$$

By solving the above equation, we obtain the true root:

$$Q^* = \begin{cases} Q_1 = \sqrt{\dfrac{\kappa + 10 - 4\sqrt{2 - 3\kappa - \kappa^2}}{17}} \\ Q_2 = \dfrac{\kappa+2}{4Q_1} - \dfrac{5Q_1}{4} \\ Q_3 = Q_1 + Q_2 \end{cases}$$

Where $-2 < \kappa \leq 0.5$

Specially, when $\kappa = 0.5$, Q_2 =0 which indicates no airflow will go through the opening 2.

- Flow Mode D

The governing equation can be written as follows:

$$\begin{cases} Q_1^2 + 2Q_2^2 = -\kappa \\ Q_2^2 - 2Q_1Q_2 = 1 \end{cases} \qquad (14)$$

Solving this equation, we can get:

$$Q^* = \begin{cases} Q_1 = \sqrt{\dfrac{-5\kappa - 2 - 4\sqrt{(\kappa-2)(\kappa+1)}}{9}} \\ Q_2 = -\dfrac{\kappa+2}{4Q_1} - \dfrac{Q_1}{4} \end{cases}$$

Where $\kappa \leq -2$

Specially, when $\kappa = -2$, Q_1 =0 which indicates no airflow will go through the opening 1, this is unstable.

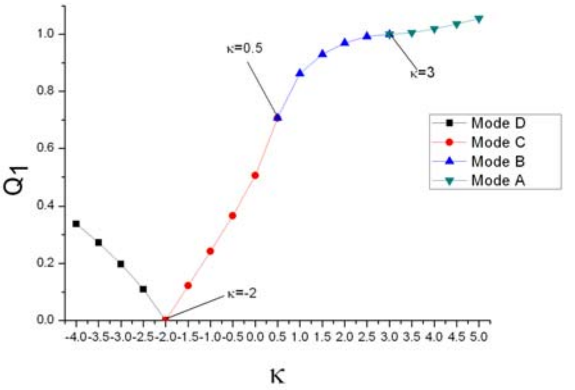


Figure4 All possible airflow modes for Opening 1

Fig.4 shows the expected airflow modes for Opening 1 under different κ values. κ =-2, 0.5 and 3 are the turning points for 4 different kinds of airflow modes. Here for the design purpose, we want to investigate how the height of Zone 2 influences the total airflow mode when the design demand is specified, i.e., to obtain the relationship between Q and χ.

We also consider two cases:

F_r >1 means that wind dominates, and F_r <1 means that buoyancy dominates. The simulation results by MIX program are compared with theoretical solutions in Fig.5-Fig.6. The diagrams show that the simulation results from MIX agree quite well with the analytical solutions.

When the wind speed is very small, e.g. F_r =0.5, the expected total airflow rate in both zones can be predicted and shown in Fig.7. The total airflow rates Q_{tot} in both two zones exhibit the similar trend as χ changes. Firstly, a critical point χ =1.5 for the minimum airflow rate exists. When χ >1.5, Q_{tot} increases with χ value, then if the height of Zone 1 is pre-assured, the increase of the height of Zone 2 will lead to the increase of natural ventilation rate in both zones. This agrees with the general idea of a high atrium design. However, when the prevailing wind is relatively high all year round, the flow pattern is highly wind-dominated, e.g. F_r =2, as depicted in Fig. 8, the increasing height of Zone 2 cannot be always contributive to the higher natural ventilation rate. In this case, the ventilation rate will decrease with χ value when $\chi < 9$. In practical terms, χ cannot be too high.

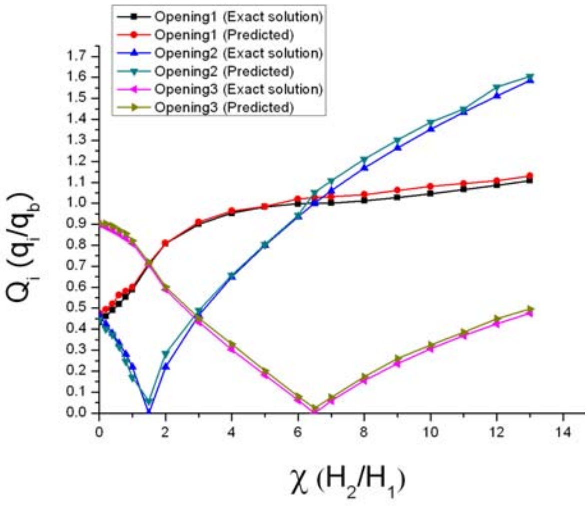


Figure5. Comparison of predicted normalized airflow rates through three openings using MIX and the theoretical solution (Fr=0.5, wind is approaching from right to left)

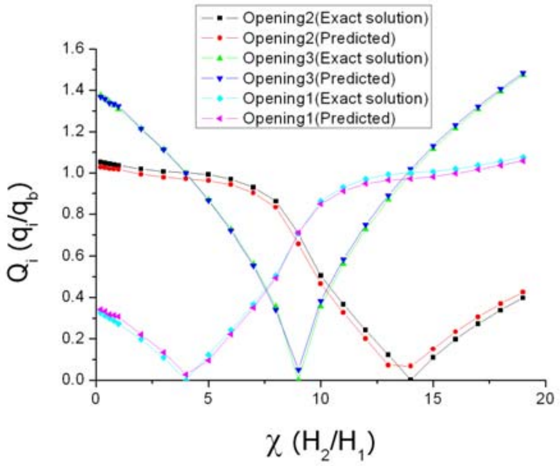


Figure6. Comparison of predicted normalized airflow rates through three openings using MIX and the theoretical solution (Fr=2, wind is approaching from right to left)

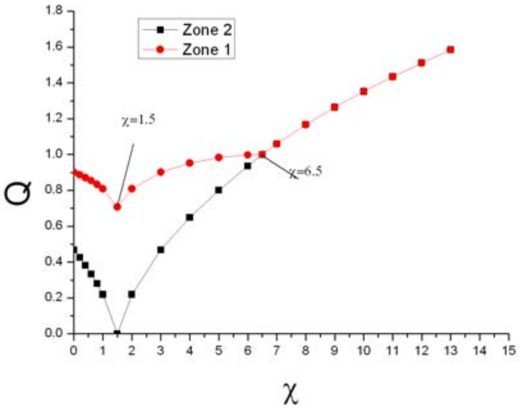


Figure7. Total airflow rate in Zone 1 and Zone2 (Fr=0.5, wind is approaching from right to left)

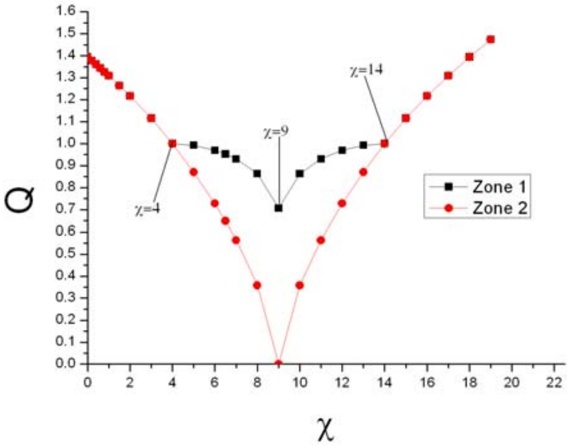


Figure8. Total airflow rate in Zone 1 and Zone2 (Fr=2, wind is approaching from right to left)

When wind is approaching from left to right (Fig.2)

When wind blows from left to right, see Fig.2, there are three possible airflow modes:

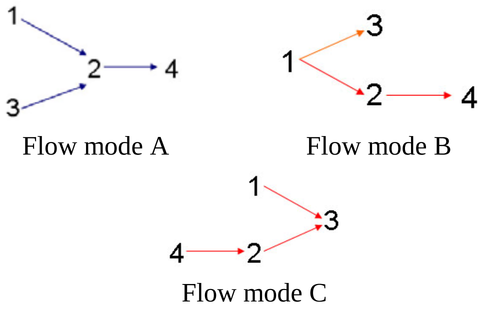


Figure7 Different airflow modes when wind is approaching from left to right

The similar theoretical analaysis can be adopted in this case. However, due to the limited length of the paper, we will just give the results of both theoretical and numerical simlulations (Fig.9and Fig.11)

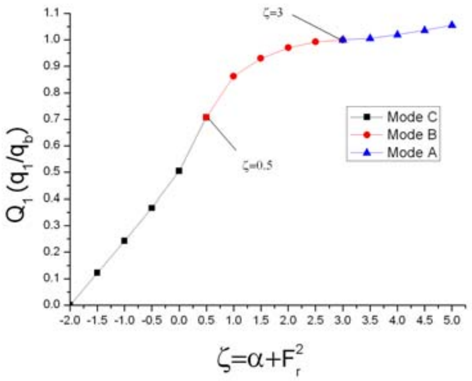


Figure9. All possible airflow modes for Opening 1

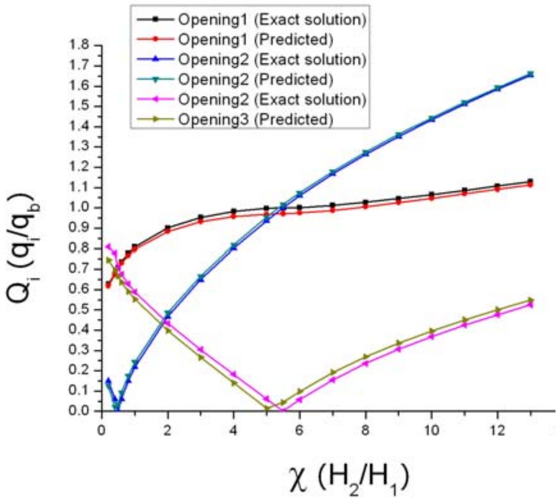


Figure10. Comparison of predicted normalized airflow rates through three openings using MIX and the theoretical solution (Fr=0.5, wind is approaching from left to right)

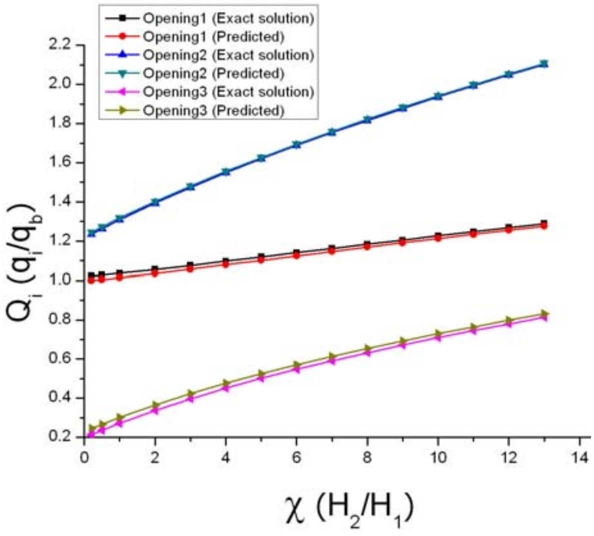


Figure11. Comparison of predicted normalized airflow rates through three openings using MIX and the theoretical solution (Fr=2, wind is approaching from left to right

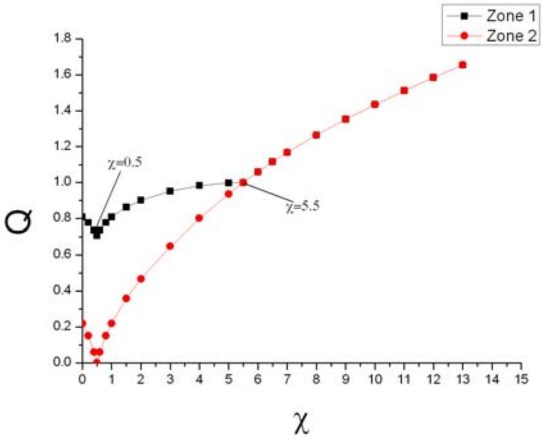


Figure12. Total airflow rate in Zone 1 and Zone2 (Fr=0.5, wind is approaching from left to right)

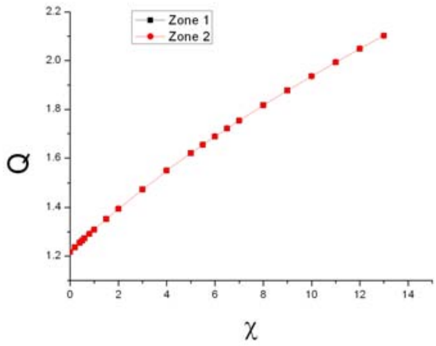


Figure13. Total airflow rate in Zone 1 and Zone2 (Fr=0.5, wind is approaching from left to right)

A good agreement between theoretical and numerical simulation results is achieved. When the wind is approaching from left to right with a relative low speed, for example F_r =0.5 here, three airflow modes will be expected with different heights of Zone 2. The total airflow rates in two zones will decrease until χ =0.5, and then will gradually rise up as χ increases. From Fig.13, we can see that there is a single airflow pattern for all χ values. This means that in relatively strong wind cases, the total airflow rate will always increase independent on the relative height of two zones.

CONCLUSION

In this paper, natural ventilation in a two-zone building subjected to combined natural forces is investigated by both theoretical and numerical methods. A new analytical solution is presented for evaluating multi-zone airflow programs. A computer program for predicting natural ventilation in multi-zone buildings, MIX, is used for the numerical simulation. Firstly, a good agreement is found between the results from the two approaches. Then it is found that wind force plays a vital role in natural ventilation design for this kind of buildings. A higher height of Zone 2, e.g. an atrium, cannot always increase the ventilation rate in zones. It also depends on the relative strength of wind and buoyancy force, as well as wind direction.

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NOMENCLATURE

c_p	pressure coefficient
H_i	middle height in local vertical coordinate for Zone *i*
N	number of zones
p_{ext}	external pressure
p_i	internal pressure for Zone *i*
$q_{j,i}$	volumetric flow rate through opening *j* in zone *i*
$q_{s,i}$	supply input by mechanical system
$q_{e,i}$	exhaust output by mechanical system
R_i	ceiling height in local vertical coordinate for Zone *i*
T_o	outside temperature
T_i	air temperature in Zone *i*
Greek symbols	
χ	height ratio
ϕ	wind direction
ρ_i	air density in Zone *i*
ρ_o	ambient air density
Δp_{tot}	total pressure loss
Subscripts	
i	zone number
o	outside
tot	Total pressure difference
w	wind

REFERENCES

Chen Z and Li Y. 2002. “Buoyancy-driven displacement natural ventilation in a single-zone building with three-level openings,” Building and Environment. 37(2):295-303

Feustel H and Dieris J. 1992. “A survey of airflow models for multizone structures,” Energy and Buildings.18:79-100

Flynn M and Caulfifld C. 2006. “Natural ventilation in interconnected chambers,” J. Fluid Mech.564:139-158

Holford J and Hunt G. 2003. “Fundamental atrium design for natural ventilation,” Building and Environment. 38(4):409-426

Ji Y, Cook M and Hanby V. 2007. “CFD modelling of natural displacement ventilation in an enclosure connected to an atrium,” Building and Environment. 42(3):1158-1172

Li Y and Heiselberg P. 2003. “Analysis methods for natural and hybrid ventilation-a critical literature review and recent development,” International Journal of Ventilation.1(4):3-20

Li Y, Delsante A and Symons J. 2000. “Prediction of natural ventilation in buildings with large openings,” Building and Environment. 35(2):191-206

Li Y and Delsante A. 2000. “Natual ventilation induced by combined wind and thermal forces,” Building and Environment. 35(2):191-206

Li Y, Duan S, Yu ITS and Wong TW. 2005. “Multi-zone modeling of probable SARS virus transimission by airflow between flats in Block E, Amoy Gardens,” Indoor Air. 15(2):96-111

Linden P, Lane-Serff G and Smeed D. 1990. “Empting filling boxes: the fluid mechanics of natural ventilation,” J. Fluid Mech.212:309-335

Lin Y and Linden P. 2002. “Buoyancy-driven ventilation between two chambers,” J. Fluid Mech.463:139-158

Yang L, Xu P and Li Y. 2006. “Nonlinear dynamic analysis of natural ventilation in a two-zone building: Part A-theoretical analysis,” HVAC&R Research.12(2):231-25