The effects of roof angle and width of adjacent buildings on wind-induced cooling ventilation of atrium spaces

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ABSTRACT

The wind-induced natural ventilation of atrium buildings with two roof openings has been investigated using computational fluid dynamics (CFD) techniques. Three possible flow patterns are identified for an atrium building with a section aspect ratio of unity: (I) when the main flow of the oncoming wind directly enters through the opening in the windward roof pitch and leaves from the leeward opening resulting in a recirculation in the space; (II) when the main flow of the oncoming wind separates at the windward top corner of the atrium and thus the airflow in the space is driven by the primary recirculation below the main flow; (III) when the main flow still separates at the windward top corner and leads to a recirculation at the roof level and the air movement in the space is driven by a secondary recirculation. For each flow pattern, the effects of the roof angle and the width of the adjacent buildings on the flow pattern and the air velocity field at occupant level are then studied and specific design guidelines are developed accordingly.

1. INTRODUCTION

Atrium spaces have been incorporated as a design element with increased frequency over recent decades (Bednar 1986), and as a result of the popularity of glass, the atrium space has become a common feature of modern public buildings. However, one major concern about the use of atrium spaces is their energy impacts: they can easily result in overheating in warm climate causing thermal discomfort due to the large glazing areas usually employed.

As a cost-effective and environmentally friendly strategy, wind-induced natural ventilation is claimed to be able to offer passive cooling benefits for atrium spaces if properly designed. Nevertheless, as the atrium type space is usually located in the centre of a building which leads to a lack of availability of openings to the outside at occupants' level, roof openings are often employed, such as those for shopping malls and office blocks.

In fact, the idea of using roof elements to enhance the ventilation of buildings is not new. Wind towers and wind catchers have been prevalent in the Middle East and North Africa for hundreds of years. Recently the effects of the vents and openings at roof level have also been noticed by a number of researchers. Bauman (1988) investigated a "jack roof" configuration using a wind tunnel and found that the jack roof can be effective in inducing internal air movement. It has also been indicated by other researchers that the shape of roof has a significant impact on the air flow patterns and air velocity distributions (Kindangen et al. 1997; Riskowski et al. 1998). Sharples and Bensalem (2001) compared several different opening scenarios in a wind tunnel and it was found that, a roof that has the largest opening, i.e. the open courtyard, has a very weak ventilation performance, particularly when the wind is perpendicular to the courtyard facade.

The present paper continues the investigation of the wind-induced ventilation through roof openings with particular focus on the systematic study of the impacts of the angle of the roof and the width of the adjacent buildings.

2. ANALYSIS OF THE AIRFLOW PATTERN IN ATRIUM SPACES

The basic case of airflow around a cubic building is first considered and the general airflow pattern is shown in Figure 1.

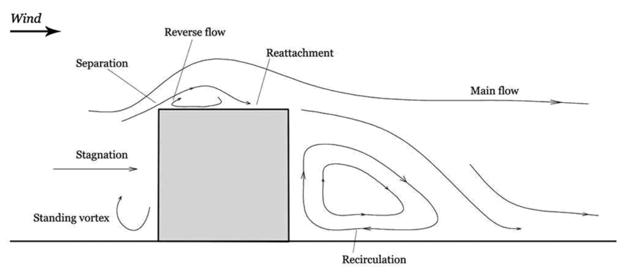


Figure 1: The airflow around a cubic building

The oncoming wind blows from the left hand side and separates at the left roof corner when it meets the building. This results in a stagnation area at the lower level near the ground in front of the building, and as the main flow over the building has an angle from the top surface other than being parallel to it, a reverse flow is incurred on the roof. The flow will reattach to the roof after a certain distance and a recirculation is formed behind the building. If a triangular roof is employed instead of the flat roof, then several different scenarios would occur depending on the roof angle. When the roof angle is very large, the roof will intrude into the main flow and thus the separation point will move from the intersection of the left edge of the roof and the windward wall to the apex of the roof. Under this circumstance part of the main flow of the wind will go directly through the roof openings and drive a recirculation in the space, as illustrated in Figure 2 (I). This airflow pattern has previously been identified as “skimming flow” by Oke (1988). When the roof angle is small, the separation point for the inflow is still at the corner of the roof and the windward wall. In this situation the airflow is induced by the reverse flow below the main flow (suction) if openings are provided on the roof. Depending on the direction of the air velocity at the inlet opening, two airflow patterns can be identified: for that shown in Figure 2 (II), the air coming through the inlet goes vertically to the bottom of the space, whilst for that shown in Figure 2 (III), the air flows horizontally forming a small recirculation at the roof level and the air movement in the space is driven by a secondary recirculation.

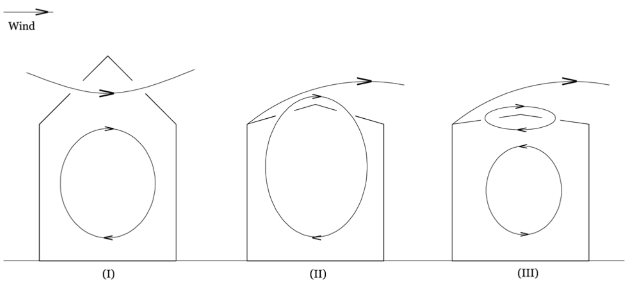


Figure 2: Three possible airflow patterns for wind-induced natural ventilation in atrium buildings with two roof openings

These three airflow patterns may have very different performance outcomes for cooling effects. Clearly the main flow is much stronger than the reverse flow and thus the flow pattern (I) usually induces the highest air velocity at the occupants’ level. As regards flow patterns (II) and (III), the air velocity magnitude is significantly influenced by the height of the centre of the recirculation: the higher the centre, the closer the air velocity at occupants’ level is to that of reverse flow and thus the higher its magnitude. It is also interesting to note that the directions of the air movement at the bottom of the space for the three flow patterns are different: that of the first two are opposite to the external wind direction while the last one is the same as the wind direction.
It can also be seen from Figure 2 that roof angle is a very important factor for the airflow pattern, since it determines the location of the separation point of surfaces exposed to positive and negative pressures. This also suggests that additional adjacent buildings will have very significant impacts on the ventilation performance of the space as their presence can change the separation point. Nevertheless, the factors affecting the transition between the flow patterns (II) and (III) still remain unclear at this stage.

3. CFD SIMULATION

CFD simulations were performed in order to verify the above analysis and understand the details of the effects of the roof angle and the adjacent buildings. The basic geometry used in CFD simulation has a similar configuration to the one illustrated in Figure 1. It is a cubic building with a width of 12*m* and a height of 12*m*. A two-dimensional simulation is carried out.
As the conditions for the openings cannot be assumed as known in the first place, the computational domain of the CFD simulation has to be extended to include some outside environment. This is illustrated by Figure 3 as follows. According to the guidelines of Hall (1997), the inlet and the top boundary is 5*H* away from the building, where *H* is the height of the building. The outflow boundary is positioned 10*H* behind the building to allow for flow development, as fully developed flow is used as a boundary condition.

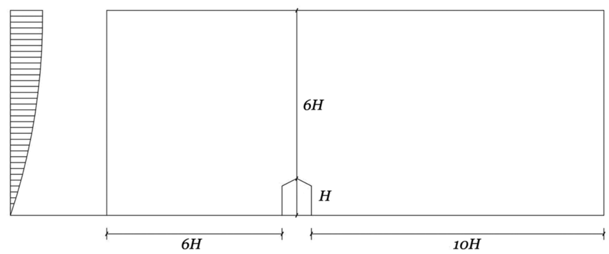


Figure 3: Schematic illustration of the computational domain for wind-induced ventilation CFD study

The boundary condition for the turbulent kinetic energy and its dissipation is described according to the formula provided by Richards and Hoxey (1993). These can be expressed by Equations (1) to (3):

$$U = \frac{U_*}{\kappa} \ln\left(\frac{z_o + y}{z_o}\right) \qquad (1)$$

$$k = \frac{U_*^2}{\sqrt{Cu}} \qquad (2)$$

$$\varepsilon = \frac{U_*^2}{\kappa (z_o + y)} \qquad (3)$$

where z_o is the surface roughness and is specified as 1.05m to represent the conditions for urban areas and the reference height is chosen as that of the roof level of the building, 12*m*. Following many widely recognised precedents, the RNG turbulence model is employed. The governing equations are discretised with the finite volume method.
A robust and commercially available CFD program, FLUENT has been used to implement the above methods.

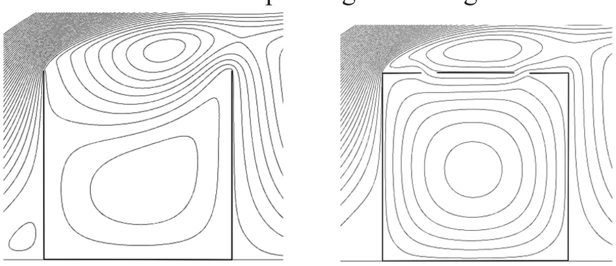
A segregated solver is used and second order approximations are used for the solution of algebraic equations. A more strict convergence criteria than the default settings, the residuals of 10^{-6} for all variables, are adopted. A validation is performed for the above settings by comparing the airflow rate of the cross ventilation in a cubic building with two openings obtained from CFD simulation with the experimental measurement by Castro and Robins (1977). A grid independence study is also carried out and the grid dimension used in this study is 340x160.

4. RESULTS AND DISCUSSIONS

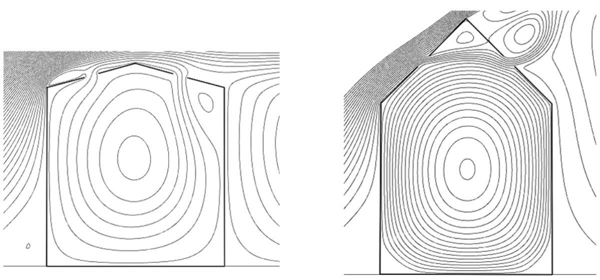
4.1 Impacts of roof angle

CFD simulation is performed for the atrium spaces with the roof angle of 0° (flat roof), 15°, 30°, 45°, 60° and one without roof, i.e. a courtyard. The openings are located in the centre of each side of the roof and have the same width of 1*m*. Adjacent buildings are not considered in this part of study.

Figures 3 to 6 illustrate the airflow patterns of the wind-induced natural ventilation for atrium spaces with several roof conditions, no roof, 0° (flat roof), 15° and 45° respectively. The courtyard and the atrium with 0° roof angle have the flow pattern (III) and the airflow patterns for 15° and 45° correspond to flow pattern (II) and (I) defined earlier. The atrium spaces with a roof angle of more than 30° generally have the same airflow pattern. This matches with the experimental observations of van Straaten et al (1965), who found that, with a low-pitched roof, both leeward and windward sides of the roof are subject to suction and the air stream approaching the building turned upwards at a roof angle which varies from about 18° to 25° depending on the height of the wall.



Figures 3 (left) & 4 (right): Airflow pattern of wind-induce natural ventilation for atria without a roof (courtyard, left) and with a roof angle of 0°(flat roof, right)



Figures 5 (left) & 6 (right): Airflow pattern of wind-induce natural ventilation for atrium spaces with a roof angle of 15°(left) and 45°(right)

Figure 7 shows the air velocity distributions at the occupants' level for each roof angle. The velocity coefficient is defined as the ratio between the local air velocity and the reference wind velocity (which is 4*m/s* at the roof level). The occupants' level is defined as the level 1.6*m* higher than the ground. It can be seen that the courtyard has the weakest ventilation performance and the highest velocity coefficient is less than 0.08. The airflow patterns of type (I) generally have the best performance among three flow patterns and the air velocity is quite evenly distributed for the majority area of the occupants' level. The air velocity obtained for flow pattern (II) when the roof angle is 15° is a little stronger than that for flow pattern (III).

The ventilation performance for the same pattern can also vary significantly. The air velocity for the courtyard is only half of that of the building with a 0° angle roof. This is because the centre of the recirculation in the courtyard is significantly reduced due to the large area of recirculation at the roof level. It is also of interest to compare the flow fields of atrium buildings with the roof of angle 45° and 60°. The building with a roof angle of 60° does not have a better performance than that of 45°: the highest air velocity at the occupants' level is nearly the same as that of 45° and the average air velocity is smaller. The reason for this is the same as that above for the difference between the roof angle 0° and the courtyard: the centre of the recirculation has changed. When the roof angle is 60°, the centre becomes very high due to the high level of openings locations. This does not make any difference for the maximum air velocity in the middle of the occupants' level; however it significantly influences the air movement at the lower corners where larger "shade" area results.

The difference of the flow patterns for roof angle 0° and 15° seem to imply that the "back flow" from the recirculation behind the building into the space is the main factor responsible for the transition between flow patterns (II) and (III). This means that the adjacent buildings on the leeward side may also impact on the ventilation performance of the space.

4.2 Impacts of adjacent buildings

The effects of the windward adjacent buildings are investigated first. It is assumed that the adjacent building has the same height as the atrium space without its roof. The windward adjacent building generally does not have any significant impact on the airflow pattern (I) (see Fig. 8 for an example); although it influences the flow field at the occupants' level (Fig. 9) because the separation point has moved forward.

Windward adjacent buildings can change the flow pattern (III) to (I) for a courtyard as illustrated in Figure

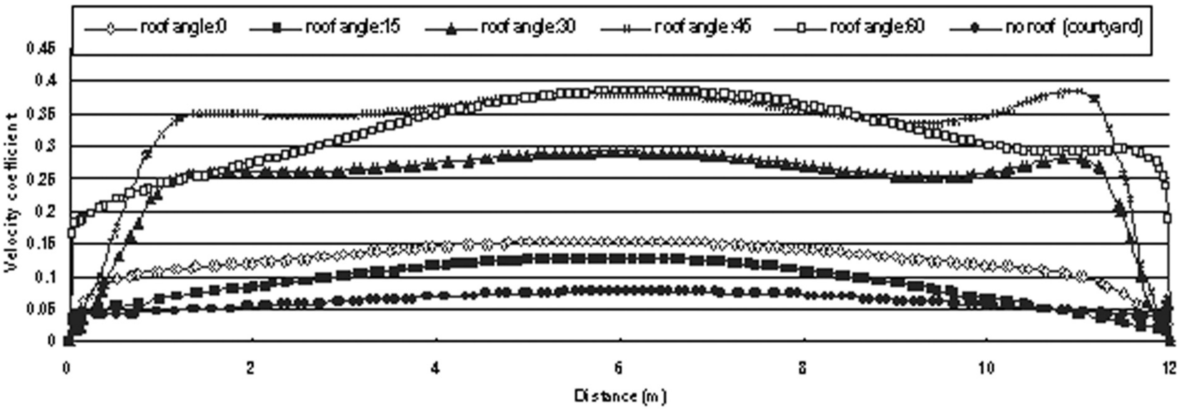
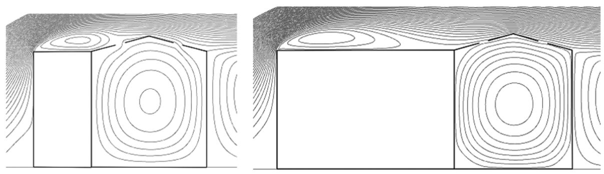


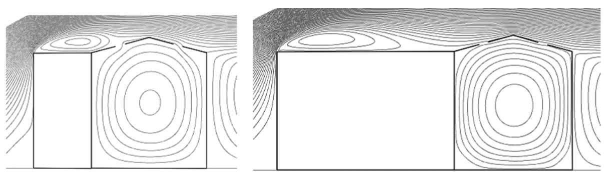
Figure 7: The distributions of the air velocity at occupants' level (1.6m) for the wind-induced natural ventilation of atrium buildings with different roof angles 4.2 Impacts of adjacent buildings

10. This is because the direction of the main flow becomes downward over the courtyard and overwhelms the recirculation behind it. It is also shown in Figure 11 that, with windward adjacent buildings, the ventilation performance of a courtyard has been greatly improved. The best performance is achieved when the width of the adjacent building is 6m, after which the separation point is very far from the courtyard and the air velocity over the courtyard is reduced.

Figures 12 shows that, when the adjacent building is not very wide (6*m*), the airflow pattern of the building with 15° roof is still the same as that of the atrium no adjacent buildings, i.e. flow pattern (II) (See Fig. 5). However, when the width of the adjacent building increases to 18*m*, the flow pattern has switched to (III) because the main flow has already re-attached to the roof when the wind meets the triangular roof (see Fig. 13).



Figures 8 (left) and 10 (right): Airflow pattern of wind-induce natural ventilation for atrium spaces with a roof angle of 45°and an adjacent building 12*m* wide on the windward (left) and for a courtyard with an adjacent building 6*m* wide (right)



Figures 12 (left) and 13 (right): Airflow pattern of wind-induce natural ventilation for atrium spaces with a roof angle of 15°and an adjacent building 6*m* (left) and 18*m* (right) wide the windward

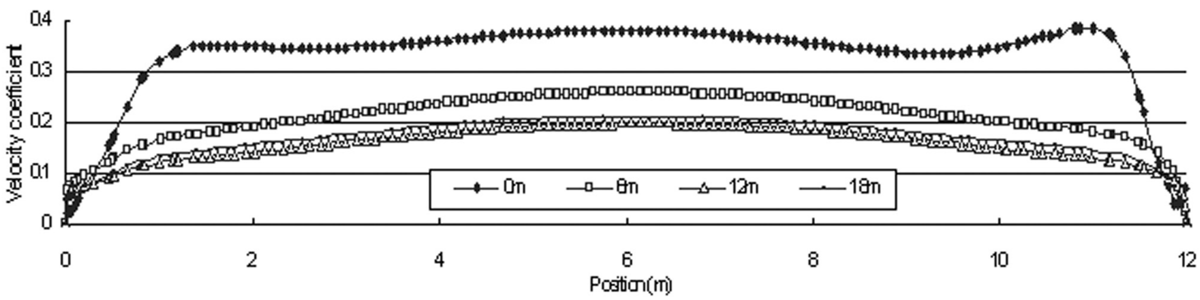


Figure 9: The distributions of the air velocity at occupants' level (1.6m) for the wind-induced natural ventilation of an atrium of 45°angle with different width adjacent buildings

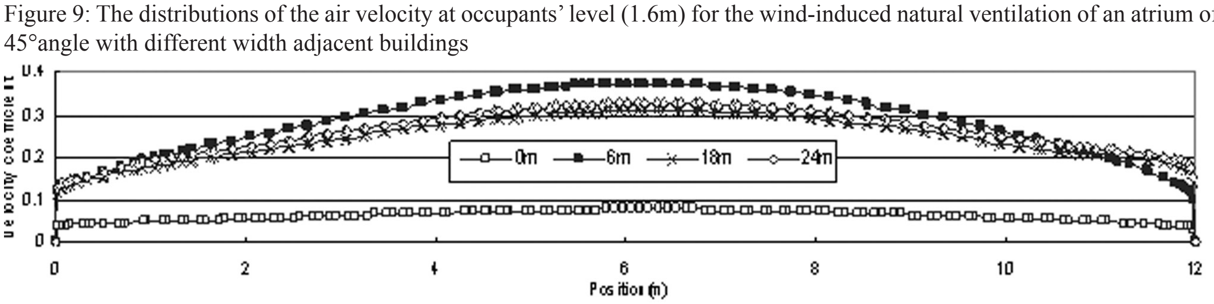
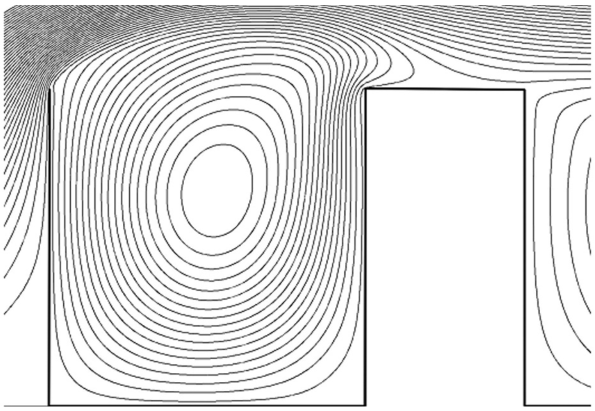


Figure 11: The distributions of the air velocity at occupants' level (1.6m) for the wind-induced natural ventilation of a courtyard with different width adjacent buildings

Then the effects of the leeward adjacent buildings are studied. Generally they do not influence the airflow pattern (I) and (II) but they can change the flow pattern (III) to (II) since they separate the recirculation area behind the building from the airflow in the atrium space (see Fig 14 for the case of the courtyard ventilation). In this way the ventilation of the courtyard could be greatly improved.



Figures 14: Airflow pattern of wind-induce natural ventilation for a courtyard with a leeward adjacent building 6*m* wide

The presence of leeward adjacent buildings can also help enhance the air velocity at the occupants' level. The flow fields of the atrium space with a 45° roof with different widths of adjacent buildings are illustrated in Figure 15. It can be seen that, the air velocity of the atrium with a 6m adjacent building is 10% higher than the one without adjacent building but further increase of the width of the adjacent building does not have a significant effect.

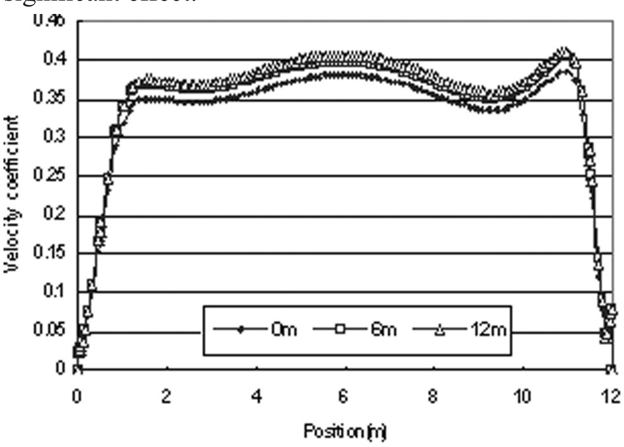


Figure 15: The distributions of the air velocity at occupants' level (1.6m) for the wind-induced natural ventilation of an atrium of 45°angle with different width leeward adjacent buildings

5. CONCLUSIONS

Three flow patterns in atrium spaces with two roof openings have been identified. According to the CFD simulations, flow pattern (I) will occur when the roof angle is more than 30° or the windward adjacent building has a large width. When the roof angle is less than 15° and the width of windward adjacent buildings is not large enough, flow pattern (II) will take place. Flow pattern (III) occurs when there is a strong back flow from the recirculation behind the building, such as in a stand-alone courtyard. Flow pattern (I) generally has the best ventilation performance whilst pattern (III) has the weakest. In order to achieve a better performance for a courtyard, it is good practice to locate some adjacent buildings along the axis of the wind direction. Atrium spaces with roof angles of around 45° and no windward adjacent buildings generally have the highest air velocity at the occupants' level. Atrium spaces with a low pitch should be placed deep in the plan with long adjacent buildings surrounding them along the wind axes to both sides to obtain increased air velocity (and comfort) in the space.

REFERENCES

Bauman, F., D. Ernest, et al. (1988). The effect of surrounding buildings on wind pressure distributions and natural ventilation in long building rows. ASHRAE Transactions 94 (Part 2): 1670 - 1695.

Bednar, M. J. (1986). *The new atrium*. New York; London, McGraw-Hill.

Castro, I. P. and A. G. Robins (1977). The flow around a surface - mounted cube in uniform and turbulent streams. Journal of Fluid Mechanics 79(2).

Hall, R. C. (1997). Evaluation of modelling uncertainty. CFD modelling of near-field atmospheric dispersion. Project EMU final report. Surrey, WS Atkins Ltd.

Kindangen, J., G. Krauss, et al. (1997). Effects of roof shapes on wind-induced air motion inside buildings. Building and Environment 32 (1).

Richards, P. J. and R. P. Hoxey (1993). Appropriate boundary conditions for computational wind engineering models using the k-e turbulence model. Journal of Wind engineering and Industrial Aerodynamics 46&47.

Riskowski, G. L., S. E. Ford, et al. (1998). Laboratory measurements of wind effects on ridge vent performance. ASHRAE Transactions 104 (1).

Sharples, S. and R. Bensalem (2001). Airflow in courtyard and atrium building in the urban environment: a wind tunnel study. Solar Energy 70 (3): 237-244.

van Straaten, J. F., S. J. Richards, et al. (1965). *Ventilation and thermal considerations in school building design*. Pretoria, N. B. R. I.