Research on the grasp of cross-ventilation performance by using
the ventilation tower in residential buildings

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Abstract
To improve the thermal environment in houses, many people prefer using natural cross-ventilation instead of an air-conditioning system. However, utilization of cross-ventilation based on two wall windows is difficult due to the influence of adjacent buildings when living within a crowded city block. We focused on a ventilation tower as a possible method for solving this problem. The purpose of this study is to evaluate the cross-ventilation performance for various shapes and heights of ventilation towers. To achieve this goal, we first performed a wind tunnel experiment using a 1:40 scale residential model. We prepared four types of ventilation towers whose heights were 1000mm, 2000mm, 3000mm, and 4000mm (actual scale). The wind pressure coefficients and ventilation rate were monitored. As a result, it was found that ventilation towers with heights over 2000mm showed nearly equivalent wind pressure coefficients and ventilation rate. In addition, we used ventilation tower models whose shapes were different (i.e., square, circle, and rectangle) and estimated the ventilation rate through computational fluid dynamics (CFD) analysis. From the CFD analysis, the square ventilation tower provided a stable ventilation rate regardless of the wind direction.

Keywords – cross-ventilation; wind pressure; wind tunnel; CFD; ventilation tower

1. Introduction

To improve the thermal environment in houses, many people prefer using natural cross-ventilation instead of an air-conditioning system. Furthermore, the utilization of cross-ventilation is an important consideration as a means for reducing energy usage in residential buildings. However, utilization of cross-ventilation using two wall windows is difficult due to the influence of adjacent buildings in a crowded city block.

As one method of solving this problem, we focused on the ventilation tower. The planar shape of the ventilation tower is square and the ventilation tower has four windows. Fig. 1 shows the conceptual ventilation tower used
in our study. Fig. 2 shows a house installed ventilation tower. In previous studies, it was found that the ventilation tower maintained a high ventilation performance in a crowded city block.

It is important to determine the optimal shape of a ventilation tower since it is assumed that the effect of pressure on ventilation tower performance varies significantly with the shape of the ventilation tower. Therefore, the purpose of this study is to evaluate the cross-ventilation performance based on various shapes and heights of ventilation towers.

![Fig. 1 Concept of ventilation tower](image1)

![Fig. 2 House installed ventilation tower](image2)

2. **methods**

2.1. Wind tunnel experiments

Experiments were conducted using the Eiffel wind tunnel at the Tokyo Polytechnic University. We performed experiments using a 1:40 scale residential model, as shown in Fig. 3, which was based on the condition of no neighboring buildings. The reference size of the ventilation tower was determined using data from previous studies.

For this study, we performed two studies. In the first study, we changed the height of the ventilation tower and surveyed the effects of the wind pressure on the ventilation tower as well as the ventilation level, as shown in Table 1. Then the opening and closing of four ventilation tower windows was conducted to again survey the effect of wind pressure on the ventilation tower, as shown in Table 2. The wind pressure was measured using a Baratron pressure gauge with the only ventilation tower windows opened. The ventilation rate was measured using the tracer gas technique. The approach flow was in accordance with a $1/4^{th}$ power profile. The wind direction angle was based on eight angles from $0^\circ$ in the south to $90^\circ$ in the east.
### Table 1. Cases of height study

<table>
<thead>
<tr>
<th>Case</th>
<th>Height</th>
<th>Ventilation tower windows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N3</td>
</tr>
<tr>
<td>VT-0.5</td>
<td>1000</td>
<td>○</td>
</tr>
<tr>
<td>VT-1</td>
<td>2000</td>
<td>○</td>
</tr>
<tr>
<td>VT-1.5</td>
<td>3000</td>
<td>○</td>
</tr>
<tr>
<td>VT-2</td>
<td>4000</td>
<td>○</td>
</tr>
</tbody>
</table>

○:open  ×:close

### Table 2. Cases of opening and closing of ventilation tower windows study

<table>
<thead>
<tr>
<th>Case</th>
<th>Height</th>
<th>Ventilation tower windows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N3</td>
</tr>
<tr>
<td>VT-NEW</td>
<td>2000</td>
<td>○</td>
</tr>
<tr>
<td>VT-EW</td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>VT-SW</td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>VT-ALL</td>
<td></td>
<td>○</td>
</tr>
</tbody>
</table>

○:open  ×:close

#### 2.2. Outline of simulation

To examine the results of the wind tunnel experiment, we reproduced the wind tunnel experiments using CFD analysis. Fig. 4 shows the CFD model. The computational conditions are given in Table 3. The turbulent flow model is a shear-stress transport (SST) k-ω model.
### Table 3. Computational conditions

<table>
<thead>
<tr>
<th>Boundary condition</th>
<th>Turbulent flow model</th>
<th>Differencing scheme</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>Inlet</td>
<td>U, V, W</td>
<td>k, ε</td>
</tr>
<tr>
<td>Wind tunnel</td>
<td>The gradients of all variables are zero</td>
<td>SST k-ω</td>
<td>SIMPLE</td>
</tr>
</tbody>
</table>

3. Results

3.1. Evaluation method of wind tunnel experiments

In this study, the ventilation performance was compared against the wind pressure coefficient ($C_p$) affecting the ventilation tower. The $C_p$ was calculated from the wind pressure measured in the experiments. We assessed the cases of a small wind pressure coefficient at a good ventilation performance since the ventilation tower was treated as the exhaust system.

$$C_p = \frac{C_w}{\frac{1}{2} \rho U^2}$$  \hspace{1cm} (1)

where $C_p$ is the wind pressure coefficient [-], $C_w$ is the wind pressure [Pa], $\rho$ is the air density [kg/m$^3$], and $U$ is the reference velocity [m/s].

The ventilation rate was compared against the dimensionless ventilation rate ($Q'$)

$$Q' = \frac{Q}{A}$$  \hspace{1cm} (2)

where $Q$ is the ventilation rate [m$^3$/s], and $A$ is the inflow opening area [m$^2$].

3.2. Ventilation tower height study

Fig. 5 shows the $C_p$ for each height. When the ventilation tower was installed on the upwind side, $C_p$ decreased. It is expected that the ventilation tower is effectively available as the exhaust system. $C_p$ in the case of the 1000mm ventilation tower is large, and the over 2000mm ventilation tower showed nearly same wind pressure coefficients in spite of changing height of the ventilation tower. This tendency was visible for the case where the ventilation tower was installed on the upwind side (90°, 135°, 180°).

As shown in Fig. 6, the wind tunnel experiment and CFD analysis both yielded similar trends. Therefore, we consider this reason from CFD analysis. Fig. 7 shows the velocity contour for the roof which is gotten by CFD analysis. From this contour, it was found that an approach flow reached the window of the over 2000 mm ventilation tower without being influenced by the separated flow at the roof surface. From these reasons, the approach flow velocity of the ventilation tower window did not change. These results explain why the over 2000 mm ventilation tower exhibited an equivalent $C_p$. 
Similar to \( C_p \), Q’ is small in the case of the ventilation tower 1000 mm high and the over 2000 mm ventilation tower is equivalent. Therefore, regarding the height of ventilation tower, it was confirmed that sufficient ventilation performance is obtained in the case of a 2000 mm ventilation tower.

![Fig. 5 Cp on each height](image1)

![Fig. 6 Relationship between experimental values and the CFD model](image2)

![Fig. 7 Velocity contour of the ventilation tower windows for each height](image3)

3.3. Opening and closing of ventilation tower windows study

Fig. 8 shows the \( C_p \) value for each wind direction angle as obtained from the wind tunnel experiments. For the case where the ventilation tower window was closed on the upwind side (i.e., Case-NEW for 0°, 45°, and 315°; Case-EW for 0°, 45°, 135°, 180°, and 225°, 315°; and Case-SW for 90°, 135°, and 180°), the \( C_p \) value is relatively small. As shown in Fig. 9, this occurs because the approach flow collided with the closed windows of the ventilation tower and separated flow occurred. In contrast, for the case where the ventilation tower window was closed on the downwind side (i.e., Case-NEW for 135°, 180°, and 225; and Case-SW for 0°, 270°, and 315°), the \( C_p \) value was relatively large. This occurred because the approach flow collided with the closed windows inside the ventilation tower (Fig. 10). When the average \( C_p \) values for the ventilation tower from Table 4 were compared, Case-VT indicated the smallest average \( C_p \). Therefore, it was determined the ventilation tower can produce large negative pressure drops when an upwind
window was closed. However, if the purpose is to obtain the stable negative pressure regardless of the wind direction, it was determined that the four windows would need to be opened.

Fig. 8 Cp in each wind direction angle

(a) Case-NEW  
(b) Case-EW  
(c) Case-SW

Fig. 9 Distribution of case-NEW (the wind direction angle is 0°)

(a) Air distribution  
(b) Pressure distribution

Fig. 10 Distribution of caseNEW (the wind direction angle is 180°)

Table 4. Avarage $C_p$

<table>
<thead>
<tr>
<th>Case</th>
<th>Ventilation tower window</th>
<th>Average $C_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-NEW</td>
<td>○ × ○ ○</td>
<td>-0.56</td>
</tr>
<tr>
<td>Case-EW</td>
<td>× × ○ ○</td>
<td>-0.68</td>
</tr>
<tr>
<td>Case-SW</td>
<td>× ○ × ○</td>
<td>-0.37</td>
</tr>
<tr>
<td>Case-VT</td>
<td>○ ○ ○ ○</td>
<td>-0.76</td>
</tr>
</tbody>
</table>
4. Case study of CFD

4.1. Outline of case study

To remove the inflow of the wall windows, we created chamber model without any wall openings. As shown in Fig. 11, the chamber model has forced inflow boundary conditions. This study was conducted without influence from neighboring buildings and conducted for both the under 30% of gross building coverage ratio and the under 50% of gross building coverage ratio cases. In the case without neighboring buildings, the computation conditions are shown in Table 3. In both the under 30% and under 50% gross building coverage ratio cases, we used cyclic boundary conditions where the mass flow rate was based on a 1/4th power profile (Fig. 12).

Fig. 11 CFD model without neighboring building

Fig. 12 CFD model used cyclic boundary

First, we studied the influence caused by the presence or absence of a ventilation tower cap and poles without considering the effects of neighboring buildings (Fig. 13). We also studied the planar shapes of ventilation tower (Table 5).

Fig. 13 The presence or absence of a ventilation tower cap and poles

<table>
<thead>
<tr>
<th>Table 5. Planar shapes and wind direction angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>caseSQ0</td>
</tr>
<tr>
<td>square</td>
</tr>
<tr>
<td>0°</td>
</tr>
</tbody>
</table>

caseCM, caseCAP, caseVT
4.2. Evaluation method of case study

The performance of the ventilation tower was evaluated based on the relationship between the dimensionless indoor pressure ($C_{pin}$) and the dimensionless ventilation rate ($Q'$). In studies regarding planner shapes, we also predicted the ventilation rate based on using a wall window and a ventilation tower window. The flowchart to predict the ventilation rate is shown in Fig. 14.

![Flowchart](Image)

**Fig. 14** Flowchart to forecast quantity of ventilation

4.3. Results of case study

Fig. 15 shows relationship between $C_{pin}$ and $Q'$ by presence or absence of the cap and poles. As shown in Fig. 15, a difference of relationship between $C_{pin}$ and $Q'$ appear in cases of the high ventilation rate. This occurred because the outflow from the ventilation tower collided with the ventilation tower cap.
Fig. 15 Relationship between $C_{\text{pin}}$ and $Q'$ by presence or absence of the cap and poles

Fig. 16 shows the relationship between the $C_{\text{pin}}$ and $Q'$ values for each planar shape without the influence of neighboring buildings. The black line shown in Fig. 16 indicates the relationship of a wall window with air inflow where the $C_p$ value is the largest. The gray line shown in Fig. 16 represents the relationship of a wall window with air outflow where the $C_p$ value is the relatively smallest value. The highest ventilation rate for all shapes is shown by caseREC0 while caseREC90 represents the lowest ventilation rate. Therefore, it was determined the rectangular shaped ventilation tower is easily influenced by wind direction angles. We confirmed the square and circular shaped ventilation towers exhibit stable ventilation rates regardless of the wind direction. We also verified the ventilation rate obtained by using a ventilation tower is 70% as much as that by using two wall windows.

As shown in Fig. 17(a), a ventilation tower of any shape can provide a ventilation rate, which is larger than that using two wall windows based on a 30% gross building coverage ratio. For a 50% gross building coverage ratio, we studied a square shaped ventilation tower that was not influenced by the wind direction and that was vest performance based on a 30% gross building coverage ratio. As shown in Figure 17(b), at 50% of gross building coverage ratio, the square ventilation tower can deliver twice the ventilation rate compared to that using two wall windows.
5. Conclusions

The cross-ventilation performance of ventilation towers over 2000 mm high exhibit small differences relative to each other; however, we can expect a high ventilation rate. In addition, it was determined a ventilation tower produces large negative pressure when an upwind window is closed. In terms of planar shapes, the square ventilation tower can provide a stable ventilation rate regardless of the wind direction. Additionally, we determined that the ventilation level would be twice that of using two wall windows.

Acknowledgment

The results obtained in the wind tunnel experiments were due to the general research theme, joint usage and joint research, and wind engineering research center of the Tokyo Polytechnic University. I am deeply grateful to all personals concerned.

References