Utilization of Cross-ventilation in High-density Urban Areas

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Abstract

The increased density of buildings in urban areas in Japan over the past several years has meant that less outdoor wind blows into buildings. Additionally, houses with many or large-size of openings are difficult to build due to concerns about security and privacy. In the present study, we have investigated the cross-ventilation characteristics of void, monitor roof and wind tower for the purpose of improving the cross-ventilation in detached houses built in high-density urban areas based on wind tunnel experiment and flow-network model calculation. At first, wind-pressure characteristics of a detached house in high-density urban areas were obtained by the wind tunnel experiment. From this result, we found that it is difficult to ensure adequate cross-ventilation in houses located in high-density urban areas by only openings in the wall surface. So, void, monitor roof and wind tower have been investigated as techniques of improving the cross-ventilation. Wind-pressure characteristics of each technique were examined by wind tunnel experiment. And rates of cross-ventilation flow from cases (i.e., void, monitor roof and normal roof) were calculated by flow-network model using wind-pressure coefficients from previous experiments. It can be concluded that void is a very effective technique for improving cross-ventilation in detached houses.

Keywords: cross-ventilation; wind tunnel experiment; void; monitor roof; wind tower

1. Introduction

A well-known ancient Japanese essayist, a Buddhist priest named Kenko, once wrote: "A house should be built with the summer in mind. In winter, it is possible to live anywhere, but a badly made house is unbearable when it gets hot." This quote, which eloquently describes Japanese housing conditions and the unbearably heat and humidity of Japanese summers, is often referred to even today. In short, Japanese traditional houses are often equipped with long eaves to prevent the summer sunshine from coming indoors, and with large open passages and sliding-wooden doors for cross-ventilation.

However, the increased density of buildings in urban areas in Japan over the past several years has meant that less outdoor wind blows into buildings. Additionally, houses with many or large-size of openings are difficult to build due to concerns about security and privacy. Nevertheless, according to a questionnaire survey, residents still wish to have more natural airflow in their houses (Imano et al., 2008, Tu et al., 2008). Therefore, it is important to develop a design that improves the amount of airflow in buildings. Shilaishi (2002) et al. demonstrated that the cross-ventilation flow rate increases and the cooling load is significantly reduced in porous buildings. Narumi et al. (2007), Ikenoue et al. (2002) and Habara et al. (2002) also showed the cross-ventilation effects of monitor-roof by conducting real house survey, wind tunnel experiments, and computational fluid dynamics.

In the present study, we have investigated the cross-ventilation characteristics of void, monitor roof and wind tower for the purpose of improving the cross-ventilation in detached houses built in high-density urban areas.

2. Wind-pressure Characteristics of Detached Houses in High-density Urban Areas

2.1 Outline of wind tunnel experiment

The current results were obtained from wind tunnel experiments conducted in the wind simulation tunnel at the University of Tokyo (Itoi et al., 1999). Fig.1. shows...
the airflow of the wind tunnel. Velocity at eaves height (59 mm) of a target house model was set at 7 m/s; the exponent of the velocity profile was set at 0.2, under the assumption that the experiment was taking place in a residential area. Fig. 2 shows the target model used in the benchmark test of the heat load simulation program, which was developed by the research committee on Thermal Environmental Engineering from the Architectural Institute in Japan. The scale of the target model was set at 1/100, and the roof gradient was ½. The model included 126 pressure measurement points. The study examined value differences measured from these pressure measurement points and the static pressure of the Pitot tube, which was placed in the wind tunnel. Wind pressure coefficients \( C_p \) were calculated via Eq. 1.

\[
C_p = \frac{P_s - P_e}{P_d}
\]  

(1)

Where \( P_d \) (standard dynamic pressure) indicates the dynamic pressure measured at eaves height without the existence of any models. \( P_s \) indicates the static pressure measured from the Pitot tube; \( P_e \) indicates the wind pressure measured from the measurement points on the model.

Fig. 3 presents two types of arrangements for the target model and its surrounding detached houses. Arrangements A and B indicate situations in which the long-side and short-side walls (gable walls) respectively of the target model are adjacent to the road. The number of surrounding houses was determined by the maximal possible numbers of houses on the turntable in the wind tunnel. All surrounding houses shared the same characteristics as the target model except for their measurement points. The building-to-land ratio for all houses was 60%. One block consisted of 10 houses, and the width of the front road was equal to the height of the eaves. The width of the road between each block was the same as the height of the house. The diameter of the turntable, 1600 mm, was 27 times the height of the eaves.

### 2.2 Examination of the reproduction ranges of surrounding buildings

First, we examined the reproduction ranges of surround buildings. Fig. 4 shows five patterns (i.e., a, b, c, d, and e) of reproduction ranges. Pattern "a" has the smallest reproduction range; additional houses on the leeward side of pattern "a" characterized pattern "b". Additional houses on the windward side of pattern "b" characterized patterns "c", "d", and "e". The experiment measured the wind-pressure coefficients from the target model in the five patterns with wind direction set as 0°.

Fig. 5 shows the difference between the five patterns of reproduction ranges in arrangement A. \( C_{p_{\Delta}} \) indicates wind-pressure coefficients measured in arrangement A. \( \Delta C_{p_{\Delta}} \) indicates the difference in the wind-pressure coefficients measured between the five patterns of
reproduction ranges in the arrangement A.

The results showed that the \( \Delta C_{pw} \) measured from the difference between patterns "a" and "b" was significant. In contrast, the \( \Delta C_{pw} \) between the patterns "c", "d", and "e", and arrangement A was smaller. Accordingly, it is appropriate to investigate the wind-pressure coefficients of the target model when three blocks are added to both its leeward and windward sides. Furthermore, because the ridgepoles of each house were parallel to wind flows of the wind tunnel in arrangement B, it is also appropriate to use arrangement B as a representation of urban areas.

2.3 Wind-pressure characteristics

Fig.6. presents the wind-pressure coefficient distribution of the target model in arrangements A and B, and without surrounding houses (i.e., case S), in a wind direction of 0º. The distribution of wind-pressure coefficients on the windward and the gable walls was wide-ranging in case S. In contrast, the values of the wind-pressure coefficients on each wall in arrangements A and B were narrowly distributed and close to zero. The average wind-pressure coefficient difference between windward and leeward walls was 0.94 in case S and 0.02 in arrangements A and B. The maximal difference in wind-pressure coefficients between windward and leeward walls was 0.06. Accordingly, ensuring adequate cross-ventilation in houses located in congested urban areas is difficult only openings in the wall are relied upon. On the other hand, wind-pressure coefficients measured on roofs were negative, regardless of wind directions or surrounding house arrangements. When comparing arrangements A and B, the absolute values and the distribution of wind-pressure coefficients were slightly different. However, the absolute values of wind-pressure coefficients on walls were much smaller, and wind-pressure coefficients on roofs were negative for all conditions.
3. Improving Techniques of Cross-ventilation in Detached Houses

3.1 Examination cases

Techniques for improving cross-ventilation effects through the use of negative pressure on roof surfaces in detached houses in arrangement A were discussed next. Fig.7 presents four cases that use different techniques (i.e., void (1), void (2), monitor roof, and wind tower).

Fig.7. Test Cases of Techniques for Improving Cross-ventilation

3.2 Wind-pressure characteristics of void

Fig.8 shows the plan and exploded figure of the void (1). The distribution of wind-pressure coefficients on wall A is shown by the heights in Fig.9. Wind-pressure coefficients were similar regardless of the varied heights. The average values of wind-pressure coefficients on all void walls (A, B, C, and D) were similar regardless of varied wind directions (see Table 1.). Accordingly, the distribution of wind-pressure coefficients inside the void was restricted. As a result, the following discussion was based on the average of wind pressure coefficients inside the void ($C_{PV}$).

Furthermore, we examined whether wind-pressure coefficients inside the void could be obtained from wind-pressure coefficients measured on the roof of the void. Fig.10 shows the locations of measurement points on the roofs of the void in void cases (1) and (2). The wind-pressure coefficients on the roof ($C_{PR}$) were represented by the average wind-pressure coefficients measured by these measurement points. Figs.11 and 12 present the results of $C_{PV}$ and $C_{PR}$ in void cases (1) and (2). In each case, the values of $C_{PV}$ and $C_{PR}$ were similar regardless of wind direction. Therefore, wind-pressure coefficients inside the void were likely to be obtained from wind-pressure coefficients measured on the roof of the void.

3.3 Wind-pressure characteristics of monitor roof

The wind-pressure coefficient of the monitor roof ($C_{PM}$) was represented by the average wind-pressure

Table 1. The Average Values of Wind-pressure Coefficients of Inner Wall Surface of the Void (1) in Arrangement A

| Wall | 0°  | 22.5° | 45°  | 67.5° | 90°  |
|------|-----|-------|------|-------|------|
| A    | -0.21 | -0.20 | -0.16 | -0.10 | -0.66 |
| B    | -0.21 | -0.20 | -0.16 | -0.11 | -0.66 |
| C    | -0.21 | -0.20 | -0.16 | -0.11 | -0.66 |
| D    | -0.22 | -0.21 | -0.16 | -0.11 | -0.65 |

wind-pressure coefficients measured on the roof of the void.

Fig.10. Measurement Points on the Roofs of the Void in Void Case (1) and (2)

Fig.11. Comparison of $C_{PV}$ and $C_{PR}$ in Void Case (1)

Fig.12. Comparison of $C_{PV}$ and $C_{PR}$ in Void Case (2)
coefficients of the front of the monitor wall, as shown by the grey area of the left-sided model in Fig.13. The wind-pressure coefficient of a normal roof \(C_{PR}\) was represented by the roofs average wind-pressure coefficients shown in the grey area of the right-sided model in Fig.13. Values of \(C_{PM}\) and \(C_{PR}\) in different wind directions are shown in Fig.14. The more measurement points toward the leeward side, the larger the negative wind-pressure coefficients obtained in both cases. \(C_{PM}\) became -0.35 when measurement points faced to the leeward side. The absolute values of \(C_{PM}\) were larger than \(C_{PR}\) regardless of wind direction. Although the wind-pressure coefficients of the normal roof were similar regardless of wind direction, the monitor roof was more efficient at improving cross-ventilation because it produced larger negative pressure.

### 3.4 Wind-pressure characteristics of wind tower

The relationship between the height of the wind tower and the wind-pressure coefficients on the top surface of the wind tower is shown in Fig.15. The wind-pressure coefficients on the top surface of the wind tower were always negative. The wind-pressure coefficients tended to converge toward a certain value with when the height of the wind tower was grater. Specifically, when the height of the wind tower reached approximately three times the height of the eaves, the wind-pressure coefficients converged.

### 3.5 Comparison of cross-ventilation flow rate according to improving techniques based on flow-network model

#### 3.5.1 Outline of Calculation

Rates of cross-ventilation flow from cases (i.e., void (1), monitor roof, and normal roof) were calculated by a flow-network model using wind-pressure coefficients obtained from previous experiments. The current calculation only considered wind ventilation. Outdoor wind velocity at eaves height was 1 m/s. Fig.16 shows the plans of calculated models. Plans of the normal roof were slightly modified in order to be comparable to the placing of the void and the monitor roof. Specifically, a ridgepole was revealed in the void space and a monitor roof was placed on the ceiling in the master bedroom. The hallway, corridor, and staircase were assumed to be in one room. Windows presented in Fig.16 were open when doing the calculation. The size of the opening facing the void was 60 cm × 90 cm; the size of the opening in the wall of the monitor roof was 120 cm × 60 cm. Discharge coefficients of openings were all 0.65.

#### 3.5.2 Calculation results

The cross-ventilation flow rates of the void case \(Q_V\) and the normal roof case \(Q_n\), which were without void or monitor roof in three different wind directions (i.e. 0°, 45°, and 90°), are shown in Fig.17.
With a wind direction of 0° and 45°, outflows toward the void from each room changed with the outflow/inflow of openings. With a wind direction of 90°, outflows toward the void and the outflow/inflow of openings were independent. Fig.18. presents the ratio of $Q_v$ and $Q_0$ in different wind directions. The effects of cross-ventilation improvements in the void case were approximately twice those of the normal roof. However, when wind directions were parallel to the ridgepole (i.e., 90° and 270°), the difference in wind-pressure coefficients between the void and the exterior walls were small. Moreover, increases in cross-ventilation flow rates were limited.

The ratio between the cross-ventilation flow rates of the monitor roof case ($Q_{M}$) and $Q_0$ is shown in Fig.19. Although improvement of cross-ventilation only showed in some rooms, the maximal cross-ventilation flow rate became more than six times that of the normal roof (e.g., in the master bedroom). Accordingly, cross-ventilation improvement due to monitor roof is very promising if done with proper consideration of the locations of the monitor roof in the house plan.

Fig.20. shows a comparison of cross-ventilation flow rates from each room averaged at wind angle between building cases. In the case of void (1), the...
flow rate increases compared with the case of a normal roof in all rooms, improving the cross-ventilation effect remarkably. In the case of the monitor roof, the improvement of the cross-ventilation effect is remarkable only in the MBR, which exists under the monitor roof. As mentioned above, a void is a very effective technique for improving cross-ventilation in detached houses, if that much space exists in the building.

4. Conclusions

In the present study, the investigation on the cross-ventilation characteristics of void, monitor roof and wind tower was conducted. The findings are listed as follows:

(1) Wind-pressure coefficients measured on roofs were negative, regardless of wind directions or surrounding house arrangements.

(2) The average values of wind-pressure coefficients on all void walls were similar regardless of varied wind directions, and these were close to that of roof surface of its equivalent position.

(3) The absolute values of wind-pressure coefficient of monitor roof were larger than that of normal roof regardless of wind direction. So, it is expected to improve cross-ventilation by using monitor roof.

(4) The wind-pressure coefficients on the top surface of the wind tower were always negative. And when the height of the wind tower reached approximately three times the height of the eaves, the wind-pressure coefficients converged.

(5) Openings set in the void wall become always outflow opening regardless wind direction. And a void is a very effective technique for improving cross-ventilation in detached houses.

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References

1) Imano, M. et al. (2008) Study on the Utility Cross-Ventilation in Guangzhou and Shenzhen in China, Journal of Asian Architecture and Building Engineering.

2) Tu, Y. et al. (2008) Cross-Ventilation Utilization of the Housing in Congested Urban Area in Taiwan, Journal of Asian Architecture and Building Engineering.

3) Shiraishi Y. et al. (2002) Enhancement Effect of Natural Cross-ventilation and Reduction Effect of Cooling Load for Porous Residential Building: Study on reduction of environmental load by residence of urban area in hot and humid region, Journal of architecture, planning and environmental engineering., No.558, Aug., 15-22 (in Japanese).

4) Narumi D. et al. (2007) Effect of the Monitor Roof on the Indoor Thermal Environment and Property of Natural Ventilation in the Room, Journal of architecture and building science journal of architecture and building science, Vol. 13, No. 26, Dec., 617-622 (in Japanese).

5) Ikenoue D. et al. (2002) Effect of the monitor roof upon the indoor thermal environment and property of natural draft in the room: Part. 3 Wind tunnel test of cross-ventilation characteristics of monitor roof, Summaries of technical papers of annual meeting of architectural institute of Japan Kinki Brunch, No. 42, Jun., 293-296 (in Japanese).

6) Habara H. et al. (2002) Effect of the monitor roof upon the indoor thermal environment and property of natural draft in the room : Part. 7 Analysis of cross-ventilation property of the monitor roof using CFD simulation, Summaries of technical papers of annual meeting of architectural institute of Japan, Aug., 755-756 (in Japanese).

7) Itoi, T. et al. (1999) Wind Simulation Tunnel at Department of Architecture, University of Tokyo, Journal of Wind Engineering, No. 81, Oct., 1-7 (in Japanese).
