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WIND-INDUCED VENTILATION OF LIGHT WELL IN HIGH-RISE APARTMENT BUILDING - INFLUENCE OF BOTTOM OPENING CONDITION ON AIRFLOW RATE

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ABSTRACT

The light well is often designed in the center of high-rise apartment buildings in Japan. This light well is an empty space without ceilings or floors from the bottom to the top, and this well is called "Void" in Japan. In this well, the exhaust from the kitchen and the gas water heater is sometimes discharged to the corridors surrounding Void, and the exhaust can pollute the air in Void. To keep the air quality in Void clean, the natural ventilation is usually depended on. The authors have made many model experiments on the natural ventilation of Void to clarify the basic ventilation characteristics such as airflow patterns, airflow rates and temperature distributions. In this paper, we investigated the effect of the size and number of bottom openings with intention to supply fresh air on the airflow rate. If two openings are located on both sides at the bottom of Void, it can be anticipated that the airflow passes through from the windward to the leeward, and the airflow rate of Void can decrease as compared with the case of only one opening. The wind tunnel test was conducted to examine this phenomenon in the wind-induced ventilation under the various conditions of the size of bottom openings and the wind directions. As a result, the airflow rates of Void with two bottom openings are obviously smaller than those with only one bottom opening.

KEYWORDS

wind-induced ventilation, light well, airflow rate, bottom opening, wind tunnel test, model experiment

INTRODUCTION

Since there have been built many high-rise apartment buildings with the deep light well in the center of those that are usually "Void" recently in Japan, many researches have been conducted to know the ventilation characteristics of Void. For instance, Hayakawa (1988), Kobayashi (1989) and Uchiumi et al. (1990) made the wind tunnel tests to clarify the wind-induced ventilation characteristics, Ohira and

Omori (1996) made a model experiment and the CFD simulation for the ventilation only by the thermal buoyancy. To know the necessary opening area, the frequency distribution of contaminant concentration should be examined. As the concentration of contaminant emitted in Void is not linear to the ventilation rate of Void, the varying contaminant concentration should be calculated from the varying airflow rate with the differential equation of mass balance of contaminant. Such calculation needs varying ventilation data, so that the airflow rate has to be calculated from the wind data previous to the calculation of concentration. The simple method to calculate the airflow rate is desired, because much computing is needed to have the data of ventilation rate ready for the calculation of contaminant concentration.

The authors have made the model experiments and calculation studies for estimating the validity of the simple calculation method of the airflow rates. As the basic research, Kotani et al. (1996) investigated the ventilation caused by thermal buoyancy and Nakamura et al. (1996) made a wind tunnel test for the wind-induced ventilation respectively. The combined effect of the wind force and the thermal buoyancy has been also tested and the validity of the calculation method by means of the multi-zone model was proved by Kotani et al. (1998). According to these results, Morihashi et al. (1999) proposed the data for the ventilation design to decide the necessary opening area based on the appearance frequency of the contaminant concentration. More experimental proofs, however, is needed on the various ventilation characteristics, especially the case that the airflow rate is expected to decrease should be checked carefully. In this paper, the additional experiments in the case of the wind-induced ventilation were conducted. If two openings are located on both sides at the bottom of Void with intention to supply the fresh air, it can be anticipated that the airflow passes through from the windward to the leeward. And the airflow rate of Void can decrease as compared with the case of only one opening. Therefore the wind tunnel test was made where its parameters are the number of bottom openings, the bottom opening area and the wind directions.

EXPERIMENTAL SET-UP

In this paper, the airflow rates and the surface pressure coefficients are measured in the wind tunnel with the scale models on the various conditions.

Experimental Model

Figure 1 shows the experimental model as a 1/250 scale model of a 41-storied apartment building in existence. As shown in the left figure, this model has the openings at the bottom and the void vertically from the bottom to the top like a duct. There are measuring points of the static pressure on the inside wall to identify the airflow rate by the pressure variation as described later. The surface pressure coefficients are also measured for the future calculation as shown in the right figure.

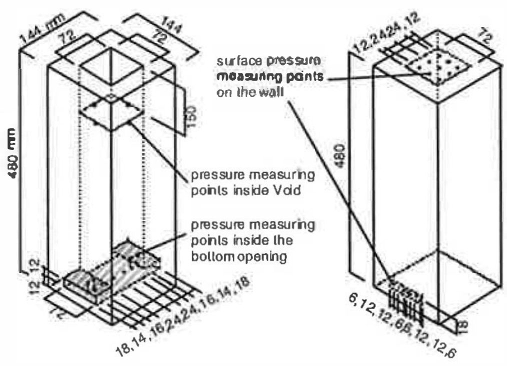
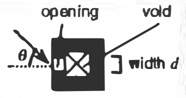
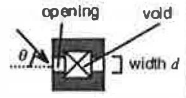


Figure 1 1/250 scale experimental model.
Left: airflow rate measurement model with Void.
Right: surface pressure measurement model

Experimental Parameters

The experimental parameters are listed in Table 1. Number of the bottom opening is one or two, provided that the position of two openings is just opposite so that the airflow passes through from the windward to the leeward. The wind directions are selected in consideration of the geometrical symmetry of the model. The bottom opening area is also changed in three levels by their width.

Table 1 Experimental parameters.

number of bottom opening		wind direction θ [deg.]	bottom opening height [mm]	bottom opening width d [mm]
1		0 45 90 112.5 157.5 180	12	12 36 72
2		0 22.5 45 67.5 75 85 90		

Wind Tunnel Test

The experimental model is set on the floor of the wind tunnel as shown in Figure 2. The large-scale turbulence is generated by the lattice and the roughness elements on the tunnel floor made the small-scale turbulence and the boundary layer. Figure 3 shows profiles of the mean velocity and the turbulence intensity. The reference wind velocity is 10m/s at 1000mm height. The mean velocity profile can be expressed by the one-forth power law.

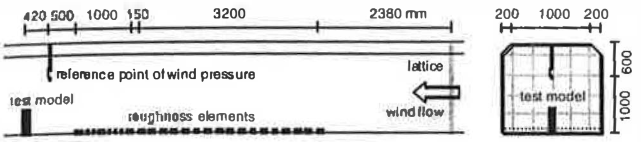


Figure 2 Wind tunnel geometry.

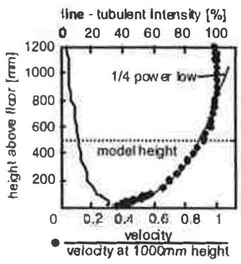


Figure 3 Approching wind profiles.

MEASUREMENT METHODS OF AIRFLOW RATE

The airflow rates through the openings and the Void are identified using the inside wall pressure of naturally ventilated model in the wind tunnel. Figure 4 and Figure 5 show the procedure to identified the airflow rate of one opening model in the cases of 12mm width and 72mm of the bottom opening. The inside wall pressures are measured in the wind-induced ventilation (See the third figure of Fig. 4 and the gray straight line of Fig. 5). Then the one opening is closed and the model is mechanically ventilated by the fan in the same wind tunnel. The inside wall pressures are measured under various forced flow rates, and the relationship between the static pressure and the flow rate is investigated like the measurement of the discharge coefficient of the opening (See the first figure of Fig. 4 and the square marks of Fig. 5 for bottom opening measurement when the wind direction is 0 degree). Whether Void is ventilated naturally or mechanically, the inside wall pressure is the same if the airflow rate is the same. Therefore the intersection point of the gray line in the wind-induced ventilation and the pressure variation curve in the forced ventilation is identified as the airflow rate of the bottom opening:

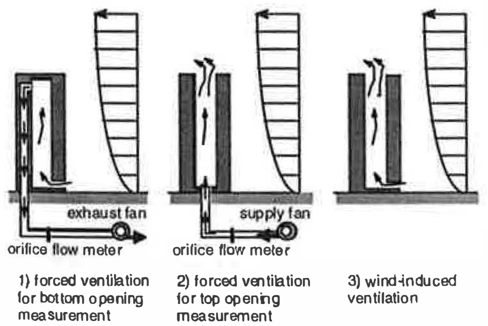


Figure 4 Airflow rate measurement of one opening model.

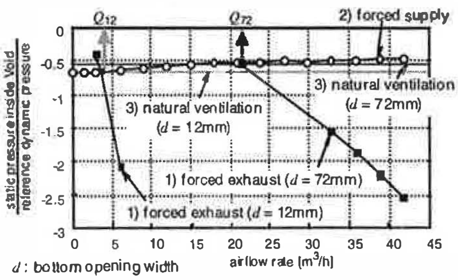


Figure 5 Variation of static pressure with airflow rate inside Void for one opening model.

Q_{12} or Q_{72}. The second figure of Fig. 4 and the circular marks of Fig. 5 are for the top opening measurement, and the identified airflow rates are expected to be the same. As a result, the intersection points are almost the same as the points for the bottom opening measurement as shown in Figure 5. This result also shows the validity of this measuring method.

Figure 6 shows a similar technique to measure the airflow rates of two opening models. The airflow rate of Void is measured by the mechanical ventilation of the top opening and wind-induced ventilation of the bottom two openings as shown in the first figure in Fig. 6. The bottom opening itself is closed and ventilated mechanically to measure its airflow rate as shown in the second figure. The airflow rate of the windward bottom opening is obtained from the addition of these two flow rates. The measurement by the tracer gas is generally used, but it is not so valid in this situation that the windward opening and the leeward opening is located at a short distance, because the gas is not fully mixed.

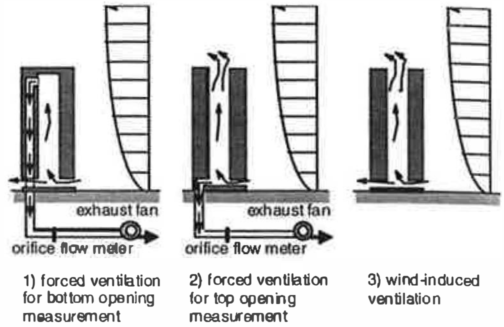


Figure 6 Airflow rate measurement of two openings model.

RESULTS AND DISCUSSION

Surface Pressure Coefficient

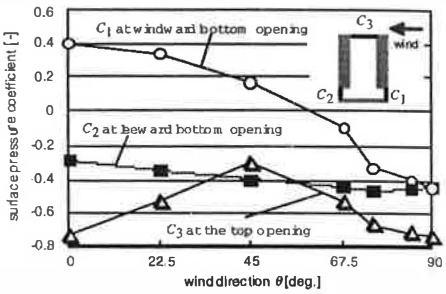


Figure 7 Surface pressure coefficient on the wall where the three openings are located.

Figure 6 shows the surface pressure coefficient where each opening is expected to locate with the mass model (See the right figure of Fig.1). C_1 and C_2 for the bottom openings are the average value of seven points and C_3 is obtained from nine points. These values are the basic data and should be used for the future calculations. In the one opening model, the airflow direction can be easily explained from the pressure differences between C_1 (or C_2) and C_3. The airflow passes from the bottom opening to the top in almost all wind directions because the bottom opening pressure C_1 is higher than that of the top opening C_3. But it must be noticed that the down-flow may occur in the case that the wind direction is around 135 degrees because the bottom opening pressure C_2 is lower than the top opening pressure C_3 (See Figure7 considering the geometrical symmetry of the model). In the two opening model, the airflow direction is not decided only by C_1, C_2 and C_3, and it depends on the balance between the internal pressure generated by the flow and the outside pressures of the flow field. Although C_1 is always higher than C_3 when the wind directions are from 0 to 90 degrees, the different flow pattern is actually observed by the flow visualization. In the case that the wind direction is from 0 to about 77 degrees, the air from the windward bottom opening is diverged to the leeward bottom opening and to the Void. But the leeward bottom opening conversely works as an inlet around 90 degrees, that is, the airflow from both bottom openings makes confluence and flows to Void. This means that the inside pressure is higher than C_2, though C_2 is higher than C_3. By the same reason, the down-flow from the top opening to the bottom opening is not seen around 45 degrees though C_3 is higher than C_2.

Airflow Rate of One Opening Model

The airflow rate of the one opening model: Q_0 is shown in Figure 8. Some data is excluded because of technical restriction, and the above-mentioned down-flow around 135 degrees is not measured either.

The airflow rate has a peek at the wind direction of 0 degree when the largest pressure difference between the bottom and the top is generated among all wind directions. The wind directional variation in the airflow rate can be explained by the variation of the pressure difference (See Figure 7). The airflow rate has positive correlation with the bottom opening width that means the opening area. These values have been already calculated by Nakamura et al. (1996) by means of the simple equation using the surface pressure coefficients, and its accuracy has been also proved practically.

Airflow Rate of Two Opening Model

When the number of bottom opening is two, three airflow rates are obtained as shown in Figure 9 for the windward bottom opening: Q_1, Figure 10 for the leeward bottom opening: Q_2 and Figure 11 for the top opening: Q_3. Q_1 shows almost same values and similar variations as the one opening model both with the wind direction and the opening width except for the opening width of 72mm. In the case that the opening width is 72mm, the outside flow field is seemed to be different from that of the one opening model because the large amount of the airflow passes though from windward to leeward opening like the cross ventilation. The negative Q_2 is obtained when the wind direction is over about 77 degrees. This means that the leeward opening works as an inlet and the confluence of the airflow from both bottom openings occurs. Q_3 shows the different tendency from Q_1 and Q_2, that is, the minimum values is obtained at the wind direction of 45 degrees. This can be understood easily from the pressure at the top opening: C_3 (See Figure 7). When the wind direction is 45 degrees, the difference between the outside pressure and the internal pressure is anticipated to minimize because the outside pressure shows maximum value. Then the decrease of the pressure difference causes the decrease of the airflow rate. When the wind direction is from 0 to 77 degrees, the maximum divergent ratio of Q_2 to Q_3 reaches about 3 to 1. This means that the airflow passing through at the bottom of Void is larger than the flow toward Void.

Effect of Number of Bottom Opening on Airflow Rate though Void

The airflow rate of Void, that is, the airflow rate through the top opening must be extremely paid attention for the IAQ in Void where the contaminant

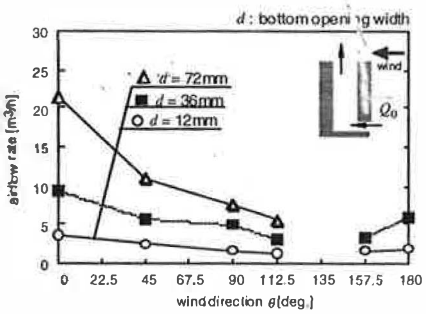


Figure 8 Airflow rate of bottom opening of one opening model: Q_0

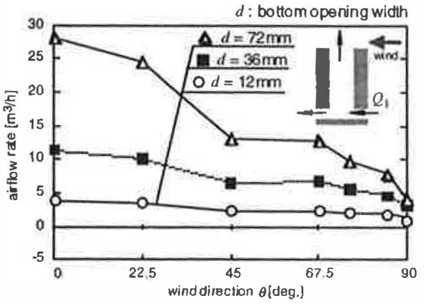


Figure 9 Airflow rate of windward bottom opening: Q_1

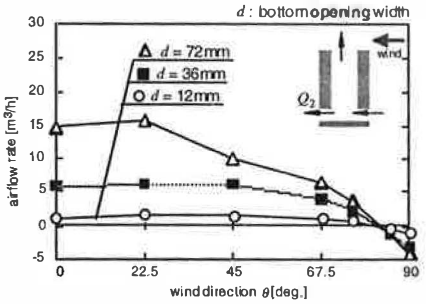


Figure 10 Airflow rate of leeward bottom opening: Q_2

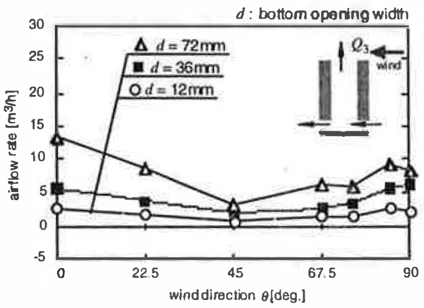


Figure 11 Airflow rate of top opening: Q_3

is likely emitted. As shown in Figure 8 and Figure 11, the airflow rate of Void with two bottom opening is quite smaller than that with one opening. Especially, the airflow rate of Void extremely decreases when the wind direction is around 45 degrees as compared with that with only one bottom opening. It should be emphasized that the total bottom opening area of two opening model is twice as large as the one opening model in these figures.

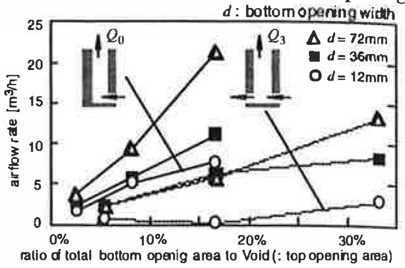


Figure 12 Airflow rate of Void: Q_0 vs Q_3

It is concluded clearly that the airflow rate of Void does not always increase with the increment of the bottom opening area when the bottom opening is located at the opposite side. The increment of the number of bottom opening causes the decrease of airflow rate contrary to the expectation that the increment of bottom opening area means the increment of supplying fresh air. This conclusion can be also seen from Figure 12 that summarized the airflow rates of Void from the viewpoint of the total area of the bottom opening.

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