Inflow Direction at Large Opening of Cross Ventilated Apartment Building

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Summary: *In case of cross ventilation through the large opening, it is well known that the inflow direction at the opening is not normal to the opening. Authors proposed the simplified prediction method of the inflow direction at the inlet opening and the airflow rate simultaneously. It is also well known that the use of general discharged coefficient (C_D) values is not suitable for the calculation of cross ventilation rate. First reason is that the simple connection of the pressure loss coefficient of an opening (ζ as the reciprocal of square C_D) in series under-estimates the airflow rate. Secondly, C_D varies according to the wind direction and the use of normal values over-estimates the airflow rate. Therefore, the proposed method uses the total pressure loss coefficient of the room (ξ) instead of ζ (or C_D). The wind tunnel tests using a three-storied apartment building model with a room were conducted to investigate the inflow direction and the flow rate. The combination of the room positions and the external wind directions make various inflow directions at the inlet opening. The results were compared with the calculated results.*

Keywords: *cross ventilation, inflow direction, wind tunnel test*
Category: *Natural and hybrid ventilation*

1. Introduction

Cross ventilation has been studied for long time by many researchers, especially Japanese researchers have been interested in this topic because the cross ventilation is common used in Japan to improve the indoor thermal environment in hot summer season [1-5]. Recently the members of IEA-ECBCS Annex 35 (HybVent) have been conducting energetic researches and many useful results have been obtained as well [6-8].

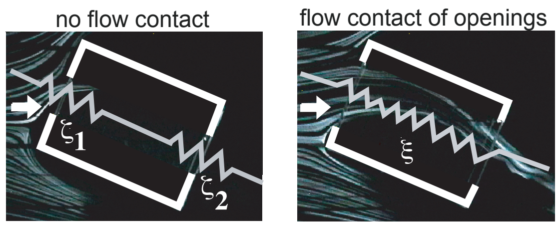
In case of cross ventilation through the large opening, it is well known that the cross ventilation makes a flow contact of windward and leeward openings as shown in Figure 1. In this situation, the use of general discharged coefficient (C_D) values is not suitable for the calculation of cross ventilation rate.

The total pressure loss coefficient of the room (ξ) becomes smaller than the connection of the pressure loss coefficient of an opening in series ($\zeta_1+\zeta_2$). Discharged coefficient (C_D) is the reciprocal of square root of $\zeta_1+\zeta_2$, so the calculation by C_D values under-estimates the cross ventilation rate. To deal with this decrease of pressure loss coefficient, Ishihara [1] proposed 'Interference factor' which is the ratio of ξ to Σζ.

Secondly, the pressure loss coefficient or C_D values of an opening varies with the inflow direction and the use of normal values over-estimates the airflow rate. Ishihara [1] also showed the experimental data citing Rydberg [10] and ξ becomes large in case of the larger argument of two openings.

Many researchers are supporting these two tendencies of the pressure loss coefficient [2-5] [9][11][12-14]. More detailed reviews about this problem are seen in Kurabuchi and Ohba [15].

Although there are many researches from the above-mentioned viewpoint, there used to be few researches to develop the simple but reasonable prediction method of the cross ventilation rate. Recently, Kurabuchi et al. [11] tried to reveal the mechanism of cross ventilation using CFD and proposed 'Local Dynamic Similarity Model of Cross Ventilation' as the systematic prediction method of flow rate. In this paper, reasonable and systematic prediction method of the cross ventilation rate through large openings was proposed and its experimental validation was carried out. 'Local Dynamic Similarity Model' consists of pressure-based description and tend to be accurate. The proposed method in this paper tends to be easy to understand aiming the practical use. The wind pressure coefficient (C_p) as in the ordinary method and the wind velocity parallel to the wall were adopted in this method.



$$\zeta_1+\zeta_2 \quad\Downarrow\quad Q=\frac{1}{\sqrt{\zeta_1+\zeta_2}}A\sqrt{\frac{2}{\rho}\Delta p}$$

$$\xi<\zeta_1+\zeta_2 \quad\Downarrow\quad Q=\frac{1}{\sqrt{\xi}}A\sqrt{\frac{2}{\rho}\Delta p}$$

Fig. 1 Use of total pressure loss coefficient instead of pressure loss coefficient of an opening.

2. Simultaneous calculation of inflow direction and airflow rate

As mentioned above, it is well known the pressure loss coefficient or C_D of an opening varies with the inflow direction. Kotani et al. [12-13] have made experiments to know ξ under various opening sizes, room sizes and wind directions. It was found that ξ also varies according to the inlet wind direction. Therefore the authors propose the simultaneous calculation method of inflow direction and airflow rate.

As shown in Figure 2, this method describes ξ as the function of inflow direction. This relation was led by authors' previous measurement using the large chamber in the calm flow field. The cubic chamber of which one side is 900 mm was used and the room model with opening was inserted at the side of the cube. The air in the cube was sucked by a mechanical fan. The relationship between the airflow rate and the total pressure difference between inside and outside of the cube were measured at the various flow rate. The inlet wind direction was controlled by means of a guided duct in front of the openings. As a result, the pressure loss coefficient of the room ξ at the various inlet wind direction was calculated by general orifice equation.

The relationship between inlet wind direction and total pressure loss coefficient by the previous measurement and its regression functions are shown in Figure 3.

The new concept of this method is use of the vector composition of the wind velocity parallel to the wall and normal to the opening. The wind velocity parallel to the wall is the velocity in front of the opening, when the opening is closed. This needs to be measured, but the authors have already had many measured data for various building shapes. Further research is now planning to prepare the reasonable function of this wind velocity.

The wind velocity nominal to the opening is the value which is the resultant airflow rate (Q) divided by opening area (A). The initial value of Q is calculated by the simple orifice equation and this value and total pressure loss coefficient of room ξ are calculated simultaneously by iteration. When the orifice equation is used, values of wind pressure coefficient (C_p) are used. C_p values should be measured as well, but authors have made a regression function for the various building shapes in the previous research.

Though this calculation needs the iteration, it is not so complicated by the use of simple vector composition. The practical use is intended and the use of the velocities parallel and normal to the wall is easy to understand.

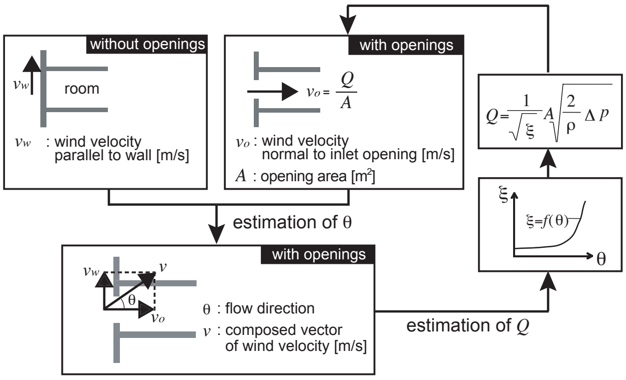


Fig. 2 Simultaneous calculation of inflow direction and airflow rate

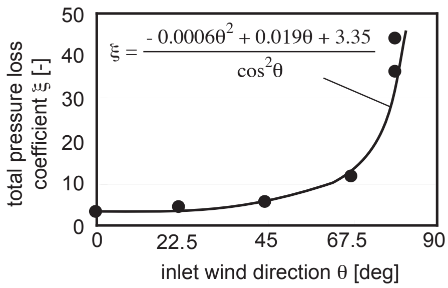


Fig. 3 Relationship between inlet wind direction θ and total pressure loss coefficient ξ.

3. Wind tunnel test

The wind tunnel tests using a three-storied apartment building model with a room were conducted to investigate the inflow direction and the flow rate at the opening. The room with the opening can be set at the different nine positions. Figure 4 and Figure 5 show the apartment model and the setup situation on the floor of the wind tunnel of which approaching flow is the atmospheric boundary layer of 1/5 power low. Figure 6 shows the wind tunnel geometry and the approaching wind profile is shown in Figure 7. The large-scale turbulence is generated by the lattice, and the roughness elements on the tunnel floor make the small-scale turbulence and the boundary layer. The reference external wind velocity is 10 m/s at 1000 mm height from the tunnel floor. The combination of the room positions and the external wind directions make various inflow directions at the inlet opening.

As the purpose of this research focuses the validation of the proposed calculation method, the experimental parameters were limited. Nine room positions and five external wind directions of 0, 22.5, 45, 67.5, 80 degree were selected as shown in Table 1.

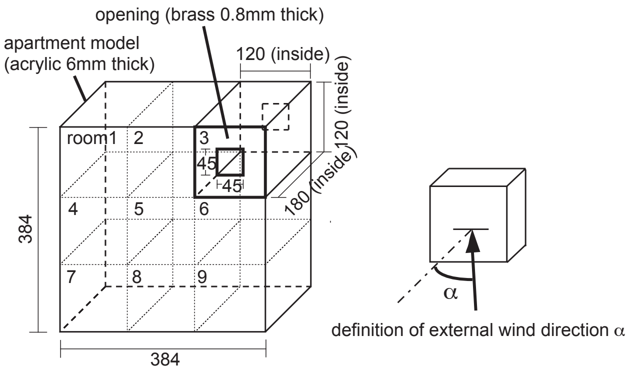


Fig. 4 Wind tunnel model of the three-storied apartment building with large opened room.

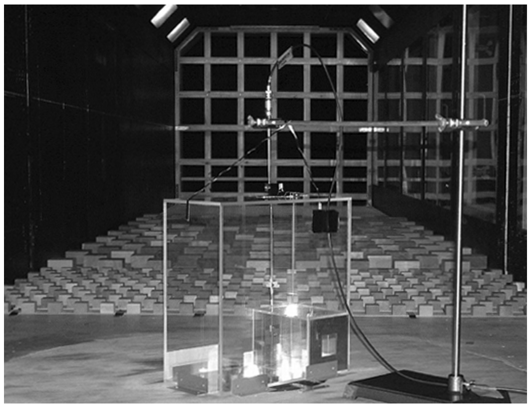


Fig. 5. Wind tunnel setup.

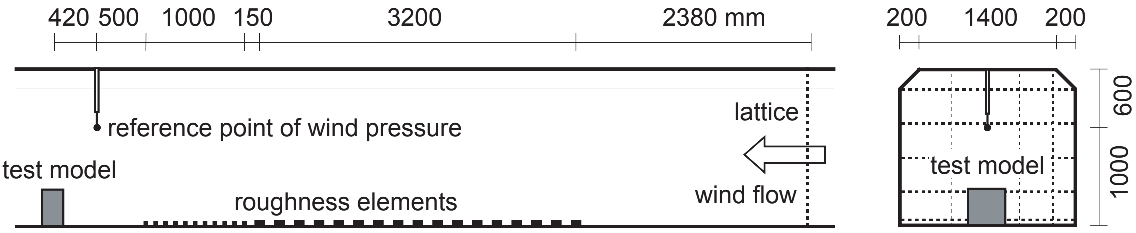


Fig. 6 Wind tunnel geometry.

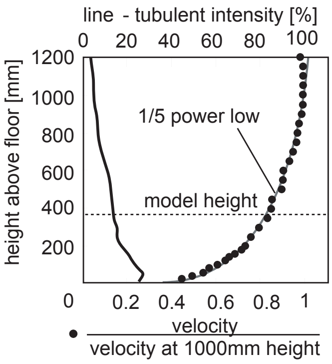


Fig. 7 Approaching wind profiles.

Table 1 Experimental condition

Room number	1, 2, 3, 4, 5, 6, 7, 8, 9 (see Fig. 4)
External wind direction [deg]	0, 22.5, 45, 67.5, 80 (see Fig. 4)

4. Measurements of wind velocities parallel to the wall and C_p values

The wind velocities parallel to the wall in front of the position where the openings locates were measured by constant-temperature hot-wire anemometer during 30 seconds with its sampling frequency of 250 Hz. The measuring points were set at the 5 mm in front of the wall. It was checked that this points locates outside the boundary layer of the wall by preliminary velocity measurements except for the case that the measuring position locates inside the wake or the separation area when the external wind direction is large. It should be noted that the measurement was conducted under the situation that openings were closed.

Figure 8 shows the measurement results of the wind velocity parallel to the wall. The reference wind velocity for the dimensionless velocity is set at the building height (384 mm). At almost all positions, the increment of the external wind directions leads to the increment of the wind velocities. This can be explained by the acceleration of the wind velocity according to the increment of the distance from the stagnation point of the building. In case that the external wind direction is 80 degree, the external flow is separated by the side wall of the building and the measuring points locate inside the wake so the wind velocity decreases.

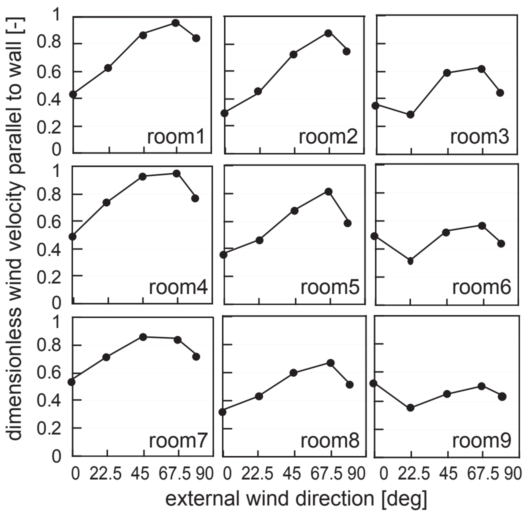


Fig. 8 Relationship between external wind direction and wind velocity parallel to wall

Figure 9 shows the difference of wind pressure coefficient (C_p) between windward and leeward opening position (ΔC_p). C_p values were measured during 30 seconds at four points where the opening locates and those averaged values as the values at each opening position were calculated. The reference dynamic pressure for C_p value is also set at the building height (384 mm). These results seem to be the reverse curve to wind velocity parallel to the wall (Fig. 8) in almost all cases. This can be understood from the viewpoint that the Bernouli's theory along the wall was realized.

These velocity and ΔC_p value are the input of the proposed calculation method.

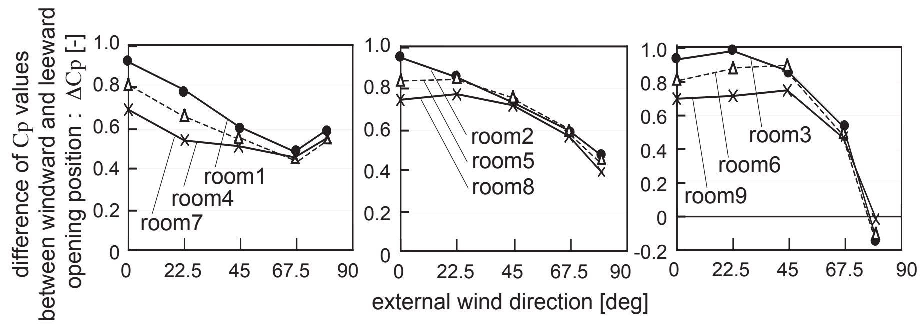


Fig. 9 Relationship between external wind direction and difference of Cp values

5. Measurement of inflow direction at the openings

The inflow direction and wind velocity at the inlet openings were measured by constant-temperature hot-film anemometer during 30 seconds with its sampling frequency of 250 Hz. This anemometer can measure the wind velocity and wind direction at the same time.

Figure 10 and 11 show the measured results of the inflow vector at the opening. In this measurement, the building was not sealed and the room opening was opened. Though these figures show the results of nine rooms in one figure, it should be noted that these were measured separately and the experiments were made to know the inflow direction in the case that only one room is set in the building. In some cases, the vectors were not drawn due to the low accuracy of the anemometer.

These vectors show the inflow direction at the opening is not normal to the opening. Only if the opening locates at the stagnation point of the building, the inflow direction is expected to be normal to the opening. In case that the external wind direction is 80 degrees, openings seem to be inside the wake or separation area of the building, so the velocities became small and the inlet direction came close to the normal to the opening. From the vectors on a vertical plane, it is suggested that the vertical stagnation point of the building locates between the second floor and the third floor at every external wind directions. As for the horizontal stagnation points, it is dependent upon the external wind direction.

These figures were reasonable from the viewpoint of the flow around and along the building.

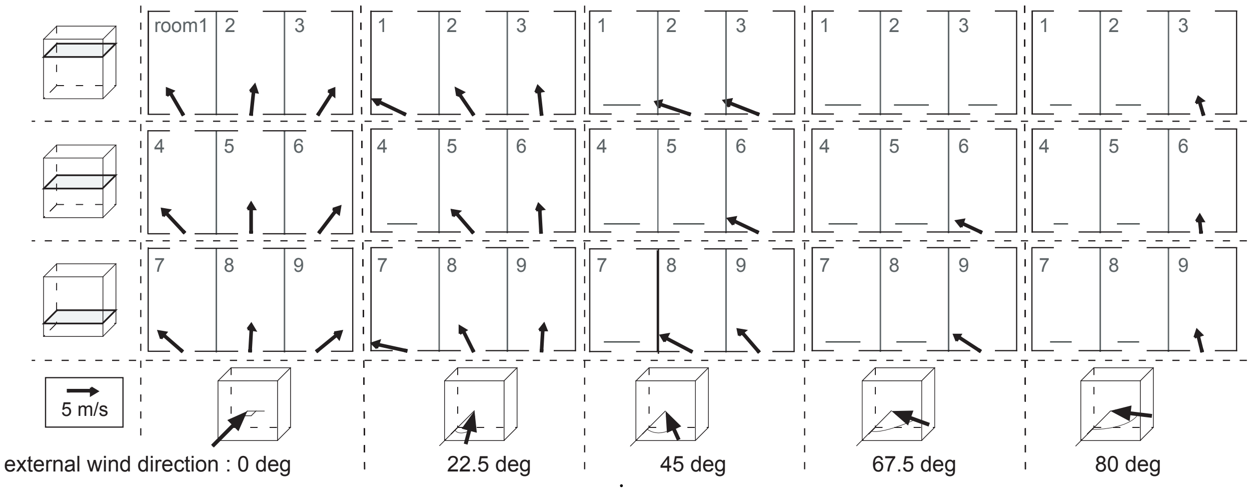


Fig. 10 Inflow vectors on horizontal plane at openings

6. Comparison with calculated results using the proposed method

The simultaneous calculation of inflow direction and the airflow rate as mentioned above were conducted. Figure 12 shows the measured inflow direction (see Figure 10 and 11) and calculated one. Plots show the measurement direction and the lines are the calculated one. There are some lacks in the measurement results.

Though the errors are very large in case that the external wind direction is 80 degree, they are in good agreement. 80 degree of the wind direction means that the openings locates inside the wake or separation area, so the different mechanism of the ventilation can occur like pulsation or turbulence diffusion. It should be also noted that the accuracy of the measurement decrease unavoidably in case of the low velocity.

This result supports that the proposed calculation method has enough accuracy of the prediction of the inlet wind direction at the opening for the most part of the external wind directions.

7. Conclusion

The simultaneous calculation of inflow direction and airflow rate was proposed and its experimental validation was conducted. This method includes the wind velocity parallel to the wall and C_p values systematically. Also the relationship between the inlet wind direction and the total pressure loss coefficient of the room are needed.

In general flow conditions that means the openings do not locate inside the wake or the separation area, the proposed method is concluded to be valid. Future studies will focus on the reasonable prediction of the wind velocity parallel to the wall and C_p values.

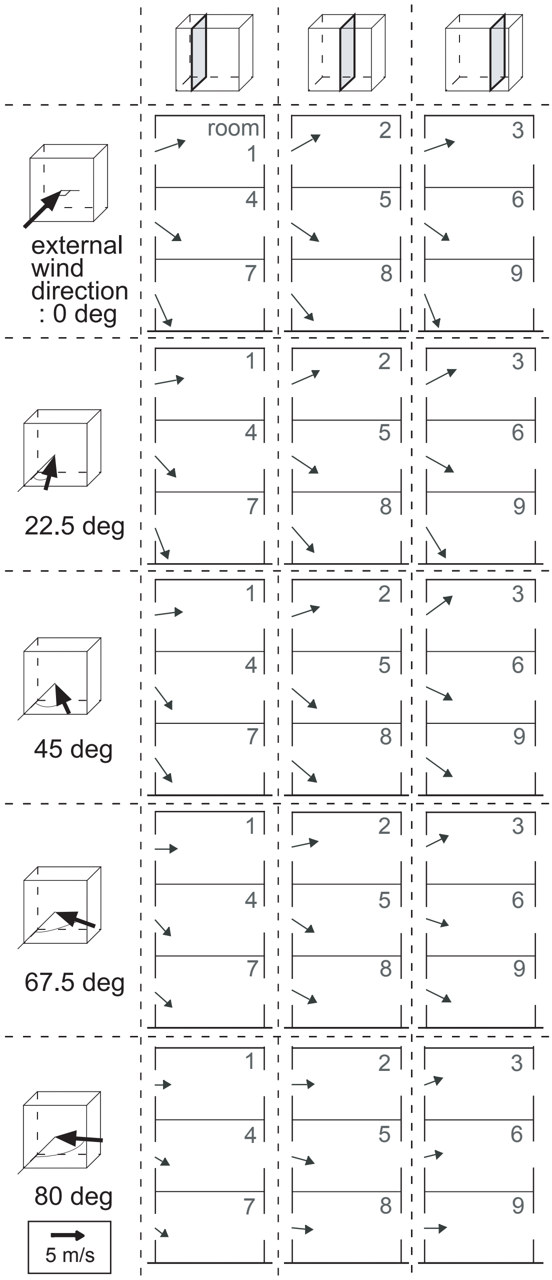


Fig. 11 Inflow vectors on vertical plane at openings

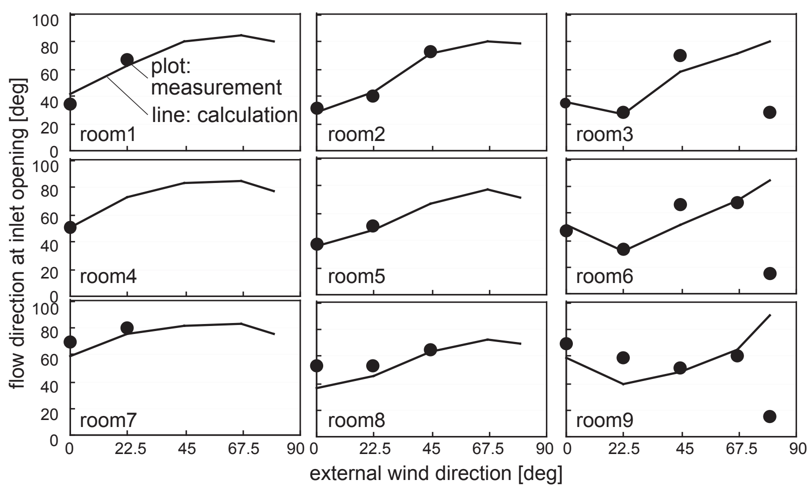


Fig. 12 Comparison between measured inflow direction and calculated one.

Acknowledgement

The part of this research is supported by TOSTEM Foundation for Construction Materials Industry Promotion, 2001- No.01-7. Authors would like to thank Mr. Kazutaka Igarashi, Mr. Jun Furukawa, Ms. Keiko Ochi and Mr. Ken-ichro Nagai for their supports in carrying out the experiments.

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