Interference Coefficient for Discharge Coefficient in Prediction of Cross Ventilation Rate through Large Openings

H. Kotani and T. Yamanaka

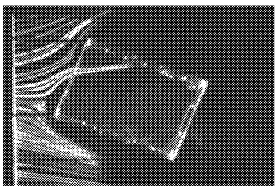
Osaka University

ABSTRACT

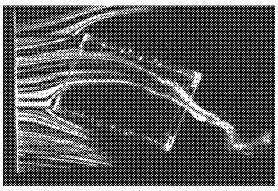
In predicting the cross ventilation rate through large openings, the use of general discharged coefficient (C_D) values for the conventional orifice equation is not suitable. 'Interference coefficient' which is the ratio of the total pressure loss coefficient of the room (ξ) to the connected value of the pressure loss coefficient of an opening in series ($\Sigma\zeta$) was used. This is a kind of correction factor. The laboratory tests were conducted to measure this interference coefficient for the various opening sizes and room shapes using scaled models. Wind tunnel experiments to know the cross ventilation rate of the model were also conducted. Calculated ventilation rates using the interference coefficient were compared with measured ones.

1. INTRODUCTION

In the case of cross ventilation through large openings, it is well known that the cross ventilation makes a flow contact of windward and leeward as shown in Figure 1 (Kotani and Yamanaka 2006). In this situation, the use of general discharged coefficient (C_D) values is not suitable for the calculation of ventilation rate.



a) Small openings



b) Large openings

Figure 1. Flow contact in cross ventilation

The total pressure loss coefficient of the room (ξ) becomes smaller than the connected value of the pressure loss coefficient of an opening in series (ζ_1+ζ_2+ζ_3+…). Discharged coefficient (C_D) is the reciprocal of square root of $\Sigma\zeta$, so the calculation by C_D values underestimates the cross ventilation rate. The main reason is that the dynamic pressure inside the room remains in the case with flow contact, while the conventional equation assumes the dissipation of the dynamic pressure inside the room. To deal with this decrease of pressure loss coefficient, Ishihara (1969) proposed "Interference coefficient" which is the ratio of ξ to $\Sigma\zeta$. This is a kind of correction factor.

In the case of two openings with the same opening area in series, the most conventional orifice equation using wind pressure is as follows.

$$Q = \frac{1}{\sqrt{\zeta_1 + \zeta_2}} A \sqrt{\frac{2}{\rho}(P_W - P_L)}$$

or

$$Q = C_D A \sqrt{\frac{2}{\rho}(P_W - P_L)} \tag{1}$$

When the total pressure loss coefficient of the room is used, ζ_1+ζ_2 is converted to ξ.

$$Q = \frac{1}{\sqrt{\xi}} A \sqrt{\frac{2}{\rho}(P_W - P_L)} \tag{2}$$

Interference coefficient is defined as follows.

$$m = \frac{\xi}{\zeta_1 + \zeta_2} = \frac{\xi}{\Sigma\zeta} \tag{3}$$

where :

m : Interference coefficient [-].

ζ: Pressure loss coefficient of an opening obtained from the chamber method conducted under the windless condition by sucking fan [-].

C_D : Discharge coefficient obtained from the chamber method [-].

ξ: Total pressure loss coefficient of a room obtained from the chamber method [-].

Q : Flow rate [m^3/s].

A : Opening area [m^2].

ρ: Density [kg/m^3].

P_W : Wind pressure on the windward wall where opening is to be provided [Pa].

P_L : Wind pressure on the leeward wall where opening is to be provided [Pa].

As shown in equation (3), the small value of the interference coefficient means that the openings "interfere" each other. When the two openings are assumed, the value of 0.5 means that the total pressure loss coefficient of the room is equal to the pressure loss coefficient of one opening, that is two opening is considered as one opening. This is fully interfered situation. If we have three openings, the interference coefficient shows 1/3 in this case. On the other hand, the value of 1.0 means that the opening do not interfere in the other opening. In this situation, the pressure loss of two openings works independently and the dynamic pressure is assumed to be dissipated inside the room.

Furthermore, 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 also showed the experimental data 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 that are the interference problem and change with in flow direction. Karava et al. (2004) reviewed the many researches from a viewpoint of the change of C_D values. Detailed reviews about this problem are also seen in Kurabuchi and Ohba (2004). However, there used to be few researches to develop the simple and reasonable prediction method of the pressure loss coefficient and the cross ventilation rate.

As the first step of developing the simple calculation method of cross ventilation rate, this paper shows the results of laboratory tests to measure this interference coefficient for the various opening sizes and room shapes using scaled models. The wind tunnel experiment to know the cross ventilation rate of the model was also conducted to valid the calculation method using the interference coefficient.

The part of this research has already presented in the previous paper (Furukawa et al. 2000, Kotani et al. 2000).

2. CHAMBER METHOD

2.1 Experimental Setup

The pressure loss coefficient will vary with room depth, opening size, condition of partition inside room and so on. The rectangular room model shown in Figure 2 was used for the measurement. For the parametric analysis, side length of the openings (L), room depth (D), with/without partition and position of the partition (d) were changed as shown in Table 1. For all cases, models have the side wall whose thickness is 6.0 mm. As for the front wall, rear wall and partition wall, 0.8 mm thick plates were provided in order to obtain sharp edges.

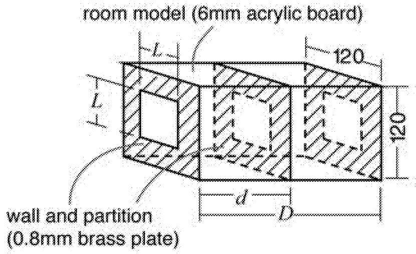


Figure 2. Room model (inner size [mm])

Table 1. Experimental condition

opening size L [mm]	15, 30, 45, 60, 90				
room depth D [mm]	60	120	180	240	360
with/witout partition and partition position d [mm]	without center 30	without center 60	without front 60 center 90 rear 120	without front 60 center 120 rear 180	without front 120 center 180 rear 240

The room model was attached to the chamber as shown in Figure 3. The inside air of the chamber is sucked out by a mechanical fan, and flow was come from the inlet opening of the room model spontaneously. The chamber is large enough to dissipate the dynamic pressure of the flow passing from the room model to the chamber. Therefore, the pressure loss was calculated by the static pressure difference between the inside and outside of the chamber. The sucking flow rates were changed in several steps, we obtained the regression curves of the flow rate and the pressure loss according with equation (2). Finally, the pressure loss coefficients were calculated by the regression curve. Only one opening was attached at the same position, and the pressure loss coefficient of an opening was calculated by the same procedure. The static pressure at the chamber wall was checked as uniform, so the measurement point of chamber wall was selected as one point.

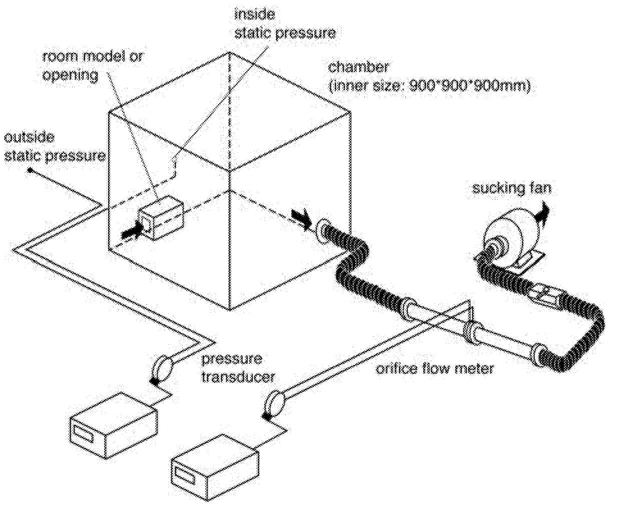


Figure 3. Setup of chamber and room model

2.2 Results and Discussions

Table 2 shows the measured pressure loss coefficient of an opening (ζ) and the condition of Reynolds number at the opening. Almost the same discharged coefficients (C_D) from 0.602 to 0.609 were obtained. These are the same as value of 0.61 that is well-known theoretical value for two-dimensional sharp-edged orifice.

Table 2. Pressure loss coefficient of one opening ζ

opening size [mm]	pressure loss coefficient ζ	discharge coefficient C_D	flow rate [CMH]	Reynolds Number at opening
15	2.71	0.607	5.29～17.5	7160～23100
30	2.76	0.602	19.3～38.3	12600～24200
45	2.76	0.602	18.5～43.1	7670～20300
60	2.75	0.603	14.0～44.1	4340～13800
90	2.70	0.609	13.5～44.6	2630～10600

Figure 4 shows the interference coefficient (m-value) obtained from equation (3). When the room depth is 60mm, m-value shows around 0.5 in the case of "without partition". This is fully interfered situation mentioned above. If there is

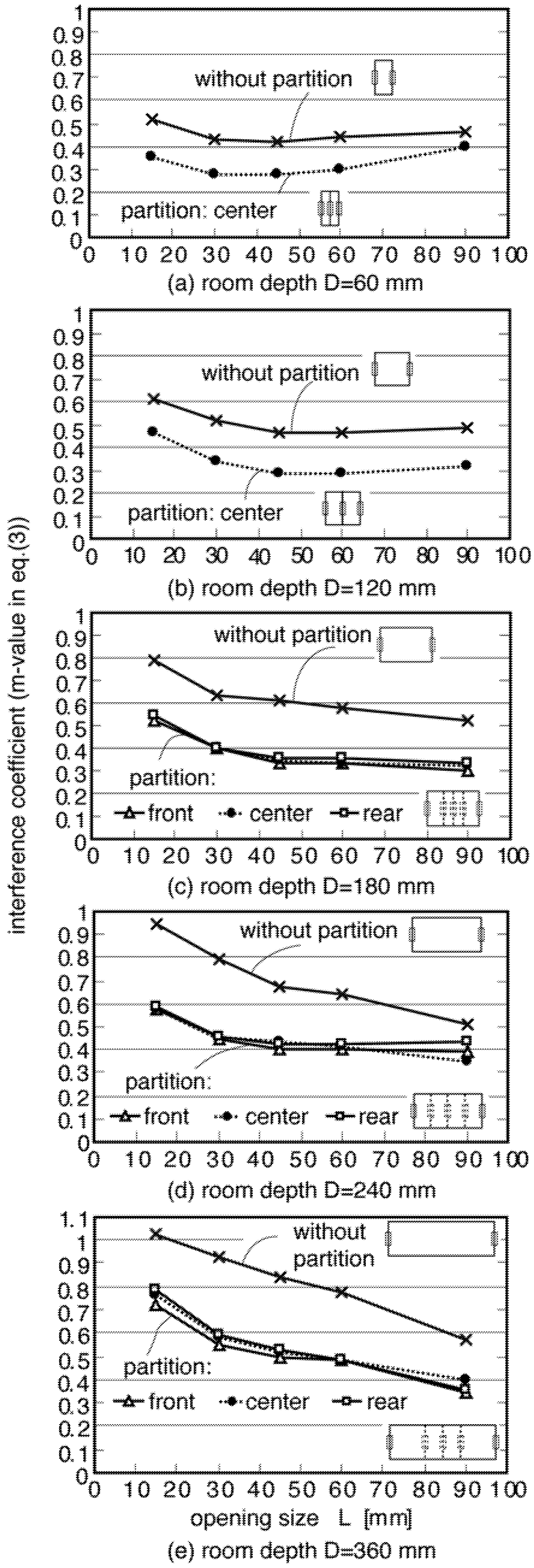


Figure 4. Influence of opening size on interference coefficient

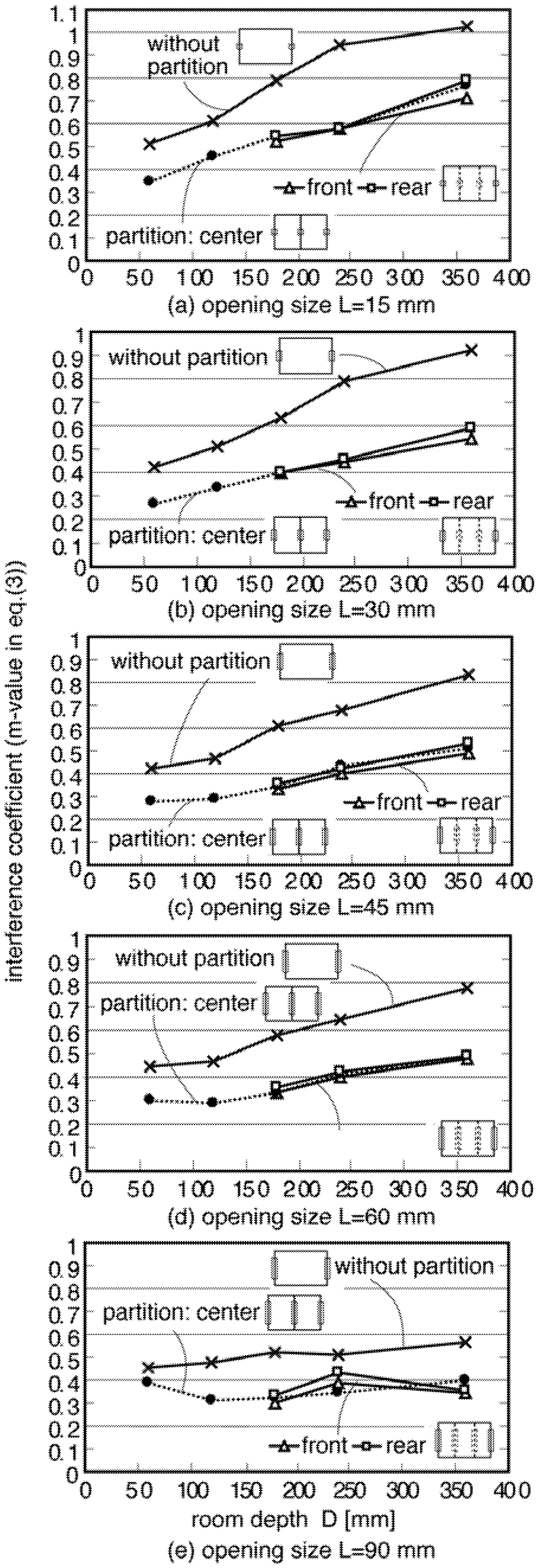


Figure 5. Influence of room depth on interference coefficient

the partition inside room in the same room depth, m-value is around 0.3-0.4. Three openings also interfere each other. In the case of larger room depth more than 240mm, m-values are influenced by the opening size. That is to say, m-value is close to 1.0 in the smallest opening size without partition, but it decreases according to the opening size, and shows the fully interfered value in the largest room depth case. There are no significant differences of m-value among the positions of the partition in all cases.

Figure 5 shows the relation between the room depth and m-value. The m-values increase according to the room depth in the cases of small opening size, that is the larger room depth can dissipate the remaining dynamic pressure inside the room and cancelled the interference of openings. When the opening size is 90 mm, m-values are constant around 0.5-0.6 in the case of "without partition" whether the room depth is small or large because the room depth is only four times of the opening size in the maximum. In all cases, m-values show around 0.5-0.6 in the case without partition and 0.3-0.4 in the case with partition when the room depth is less than about four times.

This result indicates that the interference coefficient has a possibility to be classified by the ratio of room depth to opening size. This seems to be reasonable explanation based on the jet behavior from the inlet opening. The jet from the inlet opening spreads with a certain angle by entrainment of the surrounding air, so the important factor for interference phenomenon is whether the region with high momentum, for instance potential core region or characteristics decay region, can pass through the leeward opening or not. The classification of interference coefficient by this point of view will be done in the future research.

3. WIND TUNNEL TEST

3.1 Experimental Setup

The wind tunnel experiment was conducted using the same room model as shown in Figure 2 to know the cross ventilation rate of the model. Figure 6 shows the wind tunnel setup that the room model was set at the center of tunnel. Approaching flow is uniform free flow of 10 m/s without any profiles or generating devices of turbulence.

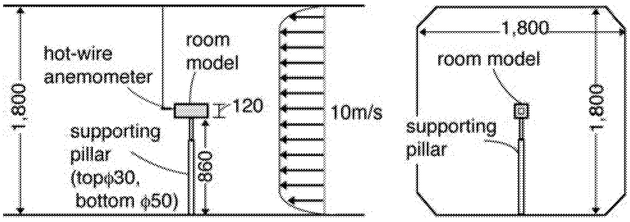


Figure 6. Wind tunnel setup

The cross ventilation rate of the room model was measured by I-type hot-wire anemometer at the leeward opening with its sampling frequency of 100 Hz and average time of 15 seconds. The anemometer approached perpendicularly to the leeward opening from the leeward side by traversing device. The measurement points are located at the same vertical plane as the leeward opening plane. The numbers of measurement points for each case is from 9 (opening size: 15 mm) to 36 (90 mm) as shown in Figure 7. The flow rate was calculated by integration of multiplying values of each measured velocity and its divided area.

The wind pressure coefficient was measured by using the sealed room model with the same size. Wind pressures at the windward and leeward wall were measured at 121 points for each wall with its spatial interval of 10 mm. The sampling frequency is 100 Hz and average time is 15 seconds. The measured wind pressure was normalized by the reference dynamic pressure of the approaching flow without the model, and the wind pressure coefficient was obtained. The average wind pressure coefficient for the opening was calculated according with the opening size of each case.

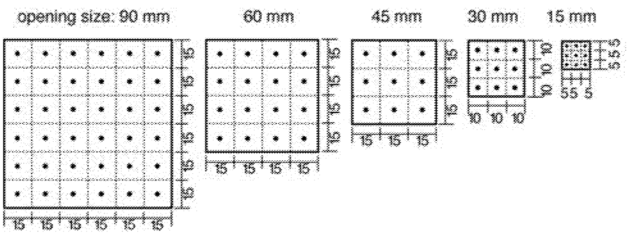


Figure 7. Measurement points of wind velocity at opening

Experimental conditions for room model are the same as above-mentioned chamber method. Additional parameter is wind direction of the approaching flow. Four directions of 0 degree, 22.5 degree, 45 degree and 67.5 degree were selected, here the 0 degree means the perpendicular direction to the windward wall from the windward side.

3.2 Results and Discussions

Figure 8 shows the difference of wind pressure coefficient between windward and leeward wall at opposite side. The opening size has no influence on the wind pressure coefficient, so the result of 45 mm is shown. Wind direction of 22.5 deg. shows maximum pressure coefficient difference and this difference highly depend on the wind direction. The room depth has also influence on the pressure coefficient difference because the large room depth means "stream-lined" shape and the drag force of the wake becomes small. The influence of wind direction is much larger than that of room depth.

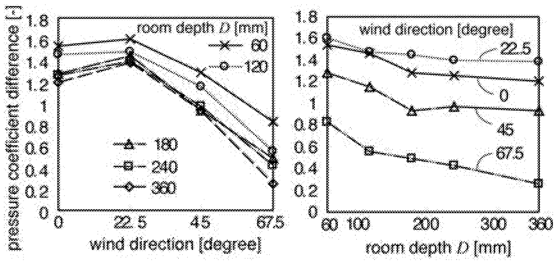


Figure 8. Difference of wind pressure coefficient (opening size: 45 mm)

Figure 9 shows the relation between measured flow rate and calculated flow rates by two methods when the opening sizes are 15, 45 and 90 mm. Measurement means the value from the velocity measurement in the wind tunnel test. Calculations use eq. (1) or (2). One is calculated by using interference coefficient (m-value) obtained from the above-mentioned chamber method. The other uses the series connection value of pressure loss coefficient of one opening ($\Sigma\zeta$). The values of pressure difference of Fig. 8 are used in both calculation methods. There are no significant differences of m-value among positions of the partition, so results of only the center partition were shown.

Measurement flow rates decrease with the increment of room depth in most cases. From the pressure difference viewpoint, it should be noted that the flow rates differ if the pressure differences are almost the same, for example the cases that the room depth is 180, 240 and 360 mm at the wind direction of 0 deg. This supports the interference of openings when the room depth is small. In the case with wind direction of 0 deg., the calculation by m-value can reproduce the increment of flow rate by interference, while the flow rate by conventional

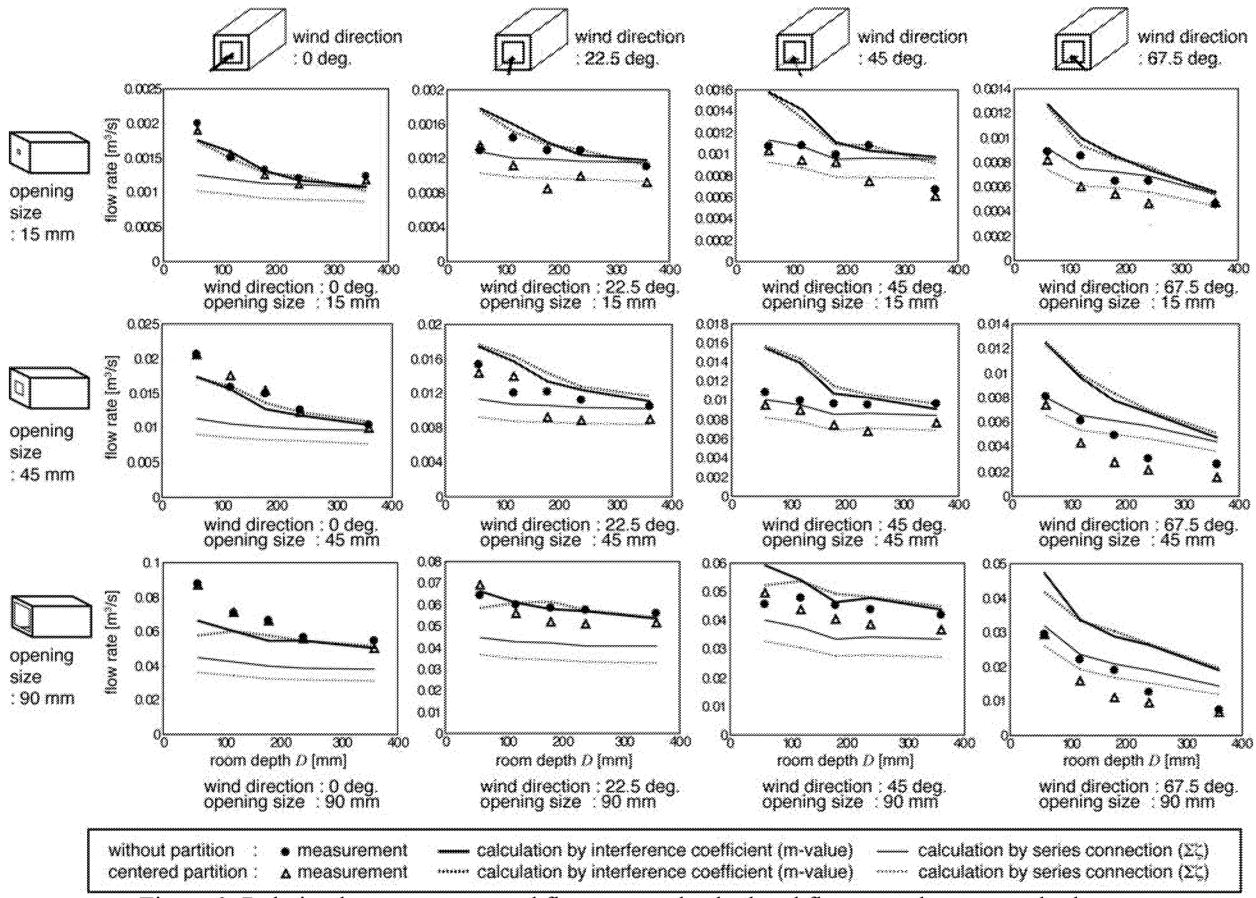


Figure 9. Relation between measured flow rate and calculated flow rates by two methods

connection values is small and does not change with the room depth. However, the calculation by m-value does not agree with the measured value in most cases that wind directions are 22.5, 45, 67.5 deg. The m-value is measured at the wind direction of 0 deg. by chamber method, so the effect of the inflow direction at the opening and inside room is not considered that authors mentioned as the further problem at Introduction chapter. This seems to be a reason of disagreement and it should be investigated more in the near future.

4. CONCLUSIONS

- The interference coefficient was measured by chamber method and the reasonable values were obtained that can be explained by the dissipation of dynamic pressure inside room.
- The interference coefficient has a possibility to be classified by the ratio of room depth to opening size according to the inflow jet behavior from the inlet opening.
- The calculation by m-value can reproduce the increment of flow rate by interference in the wind direction of 0 deg., but the consideration of inflow direction on pressure loss coefficient will be needed in the future.

ACKNOWLEDGEMENT

Authors would like to thank Mr. J. Furukawa and Mr. T. Fujii for carrying out this research.

REFERENCES

Furukawa, J., Yamanaka, T. and Kotani, H. (2000). Cross-Ventilation Rate of Building with Windows Arranged in Series –Part2. *Proc. Annual Meeting of AIJ*, D2, pp.551-552. (In Japanese)

Ishihara, M. (1969). Building Ventilation Design, Asakura Publisher. (In Japanese)

Karava, P., Stathopoulous T and Athienitis, AK. (2004). Wind Driven Flow through Openings - A Review of Discharge Coefficients, *The International Journal of Ventilation*, Volume 3, Number 3, pp.255-266.

Kotani, H., Yamanaka, T. and Furukawa, J. (2000). Cross-Ventilation Rate of Building with Windows Arranged in Series –Part3. *Proc. Annual Meeting of AIJ*, D2, pp.553-554. (In Japanese)

Kotani, H. and Yamanaka, T. (2006). Flow Visualization and Inflow Direction Measurement at a Cross-Ventilated Large Opening, *The International Journal of Ventilation*, Volume 5, Number 1, pp.79-88.

Kurabuchi T. and Ohba, M. (2004). Local Dynamic Similarity Model of Cross-Ventilation - Part1. *The International Journal of Ventilation*, Volume 2, Number 4, pp.371-382.