Local dynamic similarity concept as applied to evaluation of discharge coefficients of ventilated buildings. Part 1: Basic idea and underlying wind tunnel tests

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ABSTRACT

A model has been proposed for evaluating the discharge coefficient and flow angle at an inflow opening for cross-ventilation. This model is based on the fact that the cross-ventilation flow structure in the vicinity of an inflow opening creates dynamic similarity under the condition that the ratio of cross-ventilation driving pressure to dynamic pressure of cross flow at the opening is consistent. It was confirmed from a wind tunnel experiment that the proposed model can be applied almost regardless of wind direction and opening position. Change of pressure along the stream tube of a cross-ventilated flow was estimated from the results of Large Eddy Simulation, and was set as the basis of model preparation.

1. INTRODUCTION

In recent years, there has been a lot of interest and concern about the utilization of air flow for improving indoor thermal conditions in hot and humid rooms, which is important for energy-saving in buildings. To expand the use of natural ventilation and to establish a reliable and effective utilization method, a much more profound understanding of the mechanism of natural ventilation is required. Wind tunnel experiments have demonstrated that the discharge coefficient relating to wind pressure with ventilation flow rate varies with wind direction and opening position (Vickery and Karakatsanis, 1987, Kiyota and Sekine, 1989). However, no model has yet been presented that adequately explain how the discharge coefficient is changed. Under such circumstances, we tried in the present study to accurately identify ventilation phenomena through use of both experiments and CFD. In the process, we tried to make it clear that total pressure can be considered as a parameter specific to an opening in a manner similar to wind pressure. We then proposed a dynamic similarity model using the total pressure at the opening in addition to wind pressure and room pressure, and tried to explain how the discharge coefficient is changed.

2. LARGE EDDY SIMULATION APPLIED TO CROSS-VENTILATION

2.1 Outline of CFD and wind tunnel model experiment

Cross-Ventilation air flow is characterized by rapid acceleration and rapid deceleration. Because it is considered difficult to apply an eddy viscosity model such as the k-ε model (Kurabuchi et al., 2000), alternatively we chose Large Eddy Simulation (LES) where the Smagorinsky coefficient is regarded as constant ($C_s = 0.13$). As shown in Figure 1, the study was performed on a ventilation air flow in a building where the boundary layer flow is regarded as an approach flow. The building under study was in the form of a rectangular parallelepiped of 2:2:1. The direction of the approach flow was varied in the range of 0 degree to 67.5 degree.

2.2 Determination of stream tube shape

We tried to elucidate the structure of ventilation

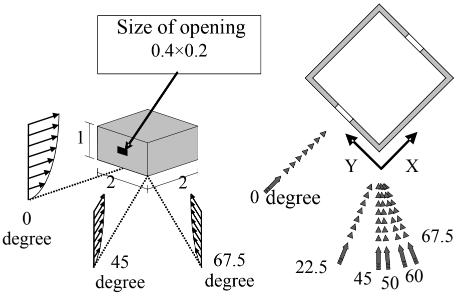

Figure 1: Building model and wind direction.

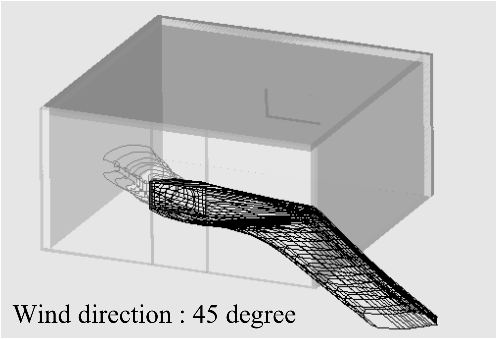

Figure 2: Shape of stream tube in the vicinity of opening.

air flow from the analysis of calculation results. First, passive markers were set out from the opening’s section. By tracing these trajectories upstream and downstream, stream tube shapes before and after the passing at the opening were determined. When the wind direction is other than 0 degree, the stream tube contacts the wall surface before it reaches the opening, as shown by the result of the case in Figure 2, where the wind direction is set to 45 degree. It is turned to a flow along the wall surface and reaches the opening. This means that in most cases the ventilation air flow may be approximated by a wall jet or boundary layer flow before it flows into the opening.

2.3 Pressure change along stream tube

The flow rate weighted average values of total pressure, static pressure and dynamic pressure in each cross-section of the stream tube were calculated. The changes of these values together with the shape of the stream tube are shown in Figure 3. From this figure, it is apparent that static pressure and dynamic pressure show extreme changes before reaching the opening when the wind direction is 45 degree or less, while the total pressure, i.e. the sum of the two, is almost constant, and pressure loss is low in the process where the wind flows along the windward wall surface. However, in the shape of the stream tube when the wind direction is 60 degree, the flow is separated at the windward corner and the flow reattaches again to the wall, and total pressure is decreased in this process.

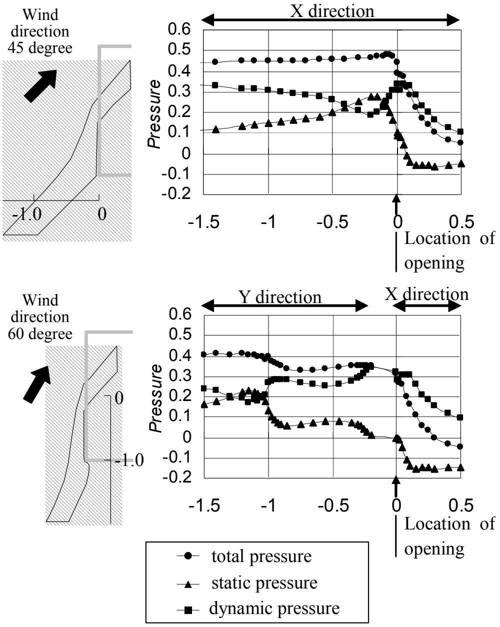

Figure 3: Identified shape of stream tube and streamwise change of pressure.

Figure 4 shows the changes of total pressure, wind pressure and room pressure at the opening where the approaching flow angle is changed. Until the wind direction reaches 45 degree, total pressure at the opening is constant. When the wind direction exceeds 45 degree, air flow is separated at the windward corner, and the total pressure is greatly decreased.

3. LOCAL DYNAMIC SIMILARITY

3.1 Modeling of the flow around the opening

Based on the results of LES, a useful model is presented, which characterizes the flow around an opening. First, for a building with cross-ventilation, total pressure at an opening for ventilation air flow is split into three components, i.e. dynamic pressure normal to the

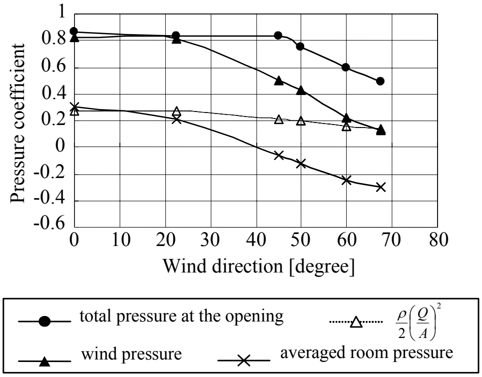

Figure 4: Evaluated pressure at different wind direction angles.

opening P_n, tangential dynamic pressure P_t, and static pressure P_S (Fig. 5). Next, room pressure P_R is picked up as an essential parameter on room side. Because there is no meaning in absolute pressure, static pressure loss “P_S-P_R”, which is the difference between the static pressure and the room pressure, is considered. Further, by taking the conveniences into account, special notice is given to “$P_n+P_S-P_R$”, i.e. the static pressure loss plus P_n. Under the condition where cross-ventilation flow rate is turned to 0, the room pressure is equal to wind pressure P_W. In this case, $P_n+P_S=P_W$. If it is supposed that the same condition exists even when there is air flow, the value of $P_n+P_S-P_R$ can be approximated as ventilation driving force P_W-P_R. Therefore, P_n, P_t and P_W-P_R are picked up as important parameters to characterize flow around the opening.

Suppose the building remains the same and only the velocity of the approaching flow is doubled. Then, all of these pressure values should be quadrupled. This is because dynamic similarity of total flow field is established. Under the condition where dynamic similarity of total flow field is established, the dimensionless values calculated by combining the three pressure values extracted above are turned to be constant. As the combination of the dimensionless values, the following values can be used, for instance: P_n/P_t corresponding to inflow angle β, and pressure loss coefficient $\zeta_n=P_n/(P_W-P_S)$ of ventilation air related to discharge coefficient Cd. With experiments performed by changing the approaching flow angle, the corresponding relation between the inflow angle and the discharge coefficient is determined.

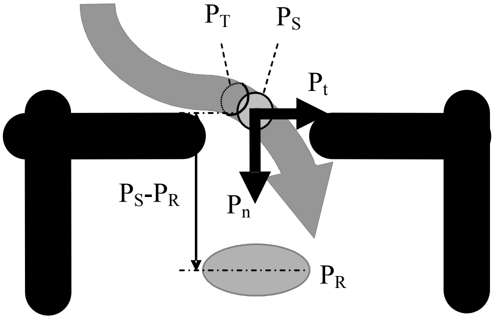

Figure 5: Characteristic pressures at opening

In case air flow conditions acting around the opening can be represented only by the three pressure values extracted above, it is expected that similarity of the flow can be established without depending on the shape of the building, position of the opening, approaching flow angle, etc. This concept may be called as local dynamic similarity in the meaning that dynamic similarity exists -not in total flow field- but only in the vicinity of the opening. In this case, a pair of two dimensionless values prepared from three pressure values represents a specific air flow condition. If these values correspond to each other at one by one, it may be deduced that, when one of them is determined, the other is automatically determined.

In order that local dynamic similarity of the flow is established, the following conditions may be required:

(a) The shape of the opening has geometrical similarity.
(b) The direction of tangential flow of the approaching flow with respect to the opening is constant.
(c) The opening is positioned on a wall surface, which is sufficiently large with respect to the size of the opening.
(d) There is no wall to hinder the diffusion of incoming air flow near the opening on room side.

It must be confirmed by the experiments how far these conditions must be satisfied in order that local similarity is established.

The inflow angle β cannot be determined unless ventilation flow rate is determined. Thus,

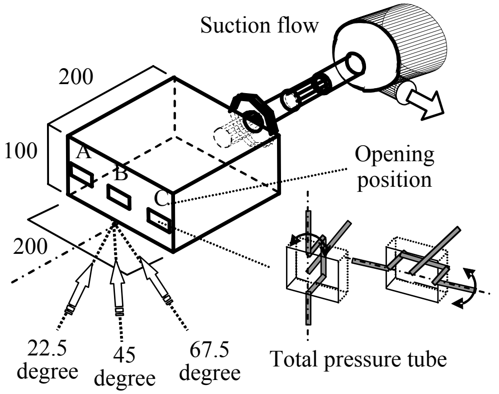

Figure 6: Experimental setup to evaluate validity of local dynamic similarity concept (unit:mm).

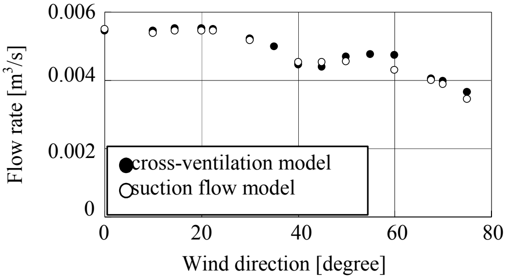

Figure 7: Comparison of suction flow rate and actual cross-ventilation flow rate.

dimensionless room pressure P_R* is defined according to the equation (1), and this is used instead of β.

$$P_R^* = \frac{P_R - P_W}{P_t} \tag{1}$$

It is defined in such manner that it corresponds to the inflow when P_R* is negative, and it corresponds to the outflow when it is positive.

3.2 Validity of suction experiment

For the purpose of quickly conducting experimental evaluation by assuming various experimental conditions for the approaching flow angle, the position of the opening, and the ventilation flow rate, an experiment was performed: A building model was connected with a suction fan on leeward side and this model was exposed to the approaching flow as shown in Figure 6. To evaluate whether actual ventilation condition can be correctly reproduced by this experimental setup, suction air flow rate was adjusted to achieve the same room pressure as the room pressure at each approaching flow angle of a ventilation model shown in Figure 1, where both room pressure and cross-ventilation flow rate had already been measured, and it was evaluated whether this was consistent with measured cross-ventilation flow rate. The results are as shown in Figure 7. Because flow rate showed good matching, it is possible to determine ventilation performance at the opening during ventilation by this method.

3.3 Validity of local dynamic similarity concept

To evaluate the validity of the proposed model, wind tunnel experiment was conducted as shown in Figure 6 by setting the position of the opening and the wind direction as variable, and the corresponding relation between P_R* and discharge coefficient was assessed. It was assumed that the openings were located at 3 positions at the central height. The end of the opening closest to the side wall concurred with the side wall, and this may have conflicts with the precondition (d) as given above.

First, it was evaluated whether the discharge coefficient (Cd's) always concurs in case P_R*→-∞. Two extreme cases were assumed: a case where stagnant surrounding condition exists around the opening and P_t=0 and suction is performed by using a fan, and a case where approaching flow angle is considered and the suction flow rate is assumed large enough to achieve $P_n \gg P_t$. The results of the comparison for each opening are summarized in Figure 8. From this figure, it has been confirmed that discharge coefficients concur well on all of the openings.

Next, measurement was performed under the condition where the value of P_t cannot be neglected. It was difficult to obtain the value of

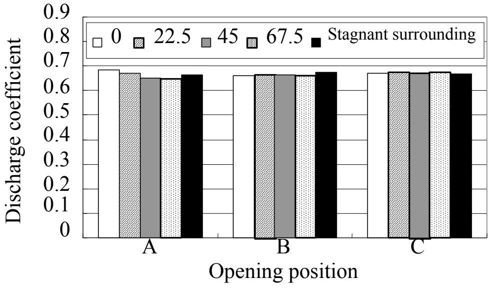

Figure 8: Comparison of Cd's in case of P_R^*→-∞.

P_t at the opening with ventilation from the measurement of wind velocity. In this respect, we adopted the following method, which did not depend on direct measurement. Total pressure P_T at the opening is $P_n+P_t+P_s$ as already described. If it is assumed that the value of P_w approximates the value of $P_n + P_s$, the value of P_t can be evaluated from the equation (2).

$$P_t = P_T - P_W \tag{2}$$

By assuming that the value of P_w can be substituted by the room pressure when the ventilation flow rate is 0, the value of P_T was determined by directly measuring the value at the center of the opening using total pressure tube.

The relation between P_R^* and Cd is shown in Figure 9. In the figure, the value of P_T as measured for each ventilation flow rate was used. As a result, it was confirmed as shown in Figure 9 that the relation between these two values can be represented by the same curve except some cases. It was extensively deviated from the curve in the case where the approaching flow angle was 67.5 degree at the windward end. In this case, there are two possibilities: the flow was separated near the opening and total pressure could not be measured accurately, and there were conflicts with the precondition of (b). Also, in case the approaching flow angle was 22.5 degree at the windward end, the values of total pressure P_T and the wind pressure P_W were very close to each other. It was difficult to evaluate the value of P_t in this experiment, and this was exempted from the study. Except these cases, it was confirmed that local dynamic similarity could be established under extensive conditions regardless of the position of the opening and the approaching flow angle.

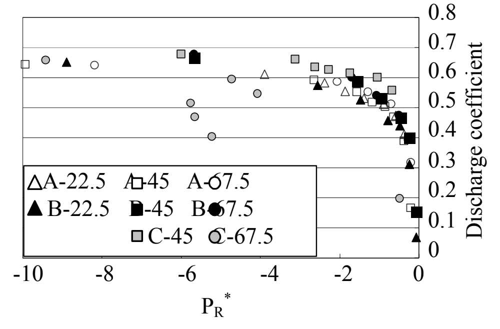

Figure 9: Discharge coefficient curves as a function of P_R^* for different wind direction angles and opening locations.

3.4 Simplification to assume total pressure

If it is necessary to have the value of P_T corresponding to the ventilation flow rate prior to the prediction of discharge coefficient, practical predicting method cannot be established. However, the value of P_T measured in the above experiment takes nearly constant value without depending on the ventilation flow rate as shown in Figure 10. In this respect, we attempted to simplify the measurement by using the value of P_T without depending on the ventilation flow rate when suction flow rate was increased as much as possible so that an inflow angle of about 90 degree could be postulated. To evaluate the validity of this method, a wind tunnel experiment was conducted by using a building model similar to the model used in the previous experiment as shown in Figure 11.

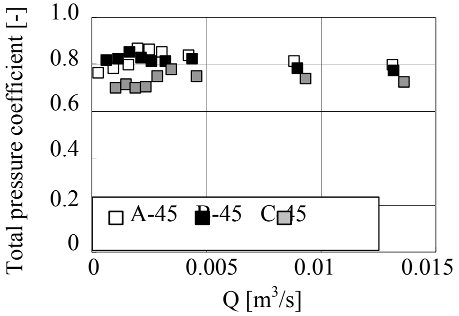

Figure 10: Relation of total pressure coefficient and suction flow rate.

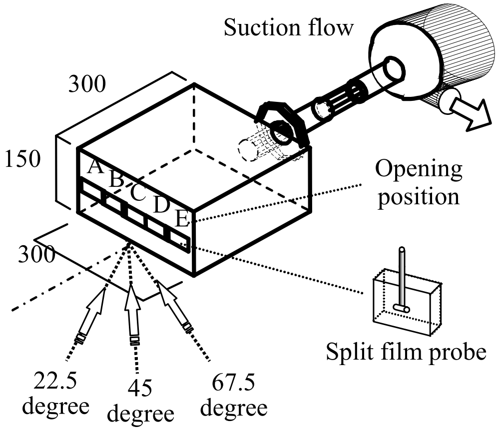

Figure 11: Experimental setup to evaluate relation of discharge coefficient and inflow angles with P_R^* (unit:mm).

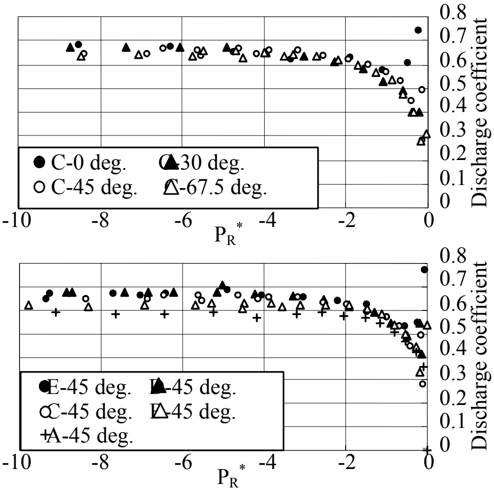

Figure 12: Discharge coefficient curves for different wind direction angles and opening locations.

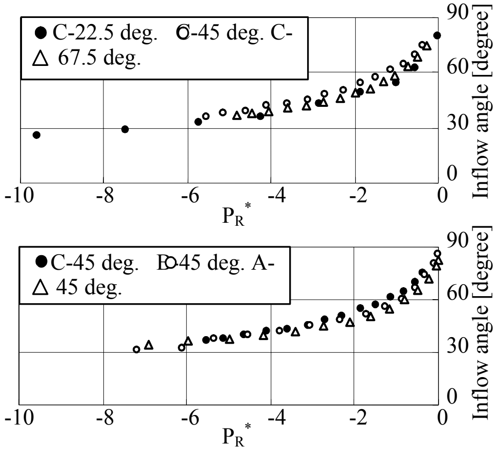

Figure 13: Inflow angle curves for different wind direction angles and opening locations.

Here, for the purpose of assessing unique matching between P_R^* and the inflow angle β, the inflow angle at the center of the opening was measured by using a split film probe.

3.5 Verification of model validity

In order to verify the validity of the proposed model, the relation between C_d and P_R* is shown in Figure 12 above, which summarizes a case where the wind direction was changed and the position of the opening was fixed at the front center of the building (opening position C). In this figure below, the relation where the wind direction was fixed at 45 degree and the position of the opening was changed is shown. According to this figure, when P_R* is less than -5, C_d is almost constant. When it is -2 or more, C_d tends to decrease rapidly. This relation remains almost constant regardless of the position of the opening and the wind direction. Similarly, Figure 13 shows the relation with the inflow angle at the center of the opening when wind direction and the position of the opening are changed. When P_R* increases, β approaches 90 degree. In this way, by applying this local dynamic similarity model, it is experimentally demonstrated that the changes of Cd and β can be explained by a single parameter P_R^*.

4. CONCLUSIONS

- Before the ventilation air flow reaches the opening, the total pressure of the approach flow is preserved almost completely regardless of the approaching flow angle if flow separation does not occur before it reaches the opening.
- The dynamic structure of the ventilation air flow becomes similar where dimensionless indoor pressure P_R* is consistent, which is expressed by the ratio of the ventilation driving force to the difference between total pressure and wind pressure at the opening.
- When P_R* is constant, the inflow discharge coefficient is consistent with the inflow angle even when the approach flow angle and the position of the opening are changed.

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