EXPERIMENTAL STUDY ON DISCHARGE COEFFICIENT OF OUTFLOW OPENING FOR PREDICTING CROSS-VENTILATION FLOW RATE

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ABSTRACT
Variation of discharge coefficients with wind direction and opening position is one of the main factors debasing accuracy of cross-ventilation flow rate prediction. The local dynamic similarity model was developed to solve this problem, and previous studies had validated it for inflow openings. In the present study, two experiments were carried out to investigate its validity for outflow openings. The experiments showed that the relationships between the discharge coefficient and a dimensionless room pressure \( P_r^* \), which was originally defined by the model, were independent of wind direction and opening position, although they were dependent on whether or not the outflow opening was in a recirculation flow region. It was thus concluded that the local dynamic similarity model was valid for outflow openings as well as inflow openings.

KEYWORDS
Cross-Ventilation, Discharge Coefficient, Wind Tunnel Experiment, Outflow Opening

INTRODUCTION
Cross-ventilation is an energy-efficient technology that is adopted to reduce energy consumption for ventilation and cooling in buildings. For successful design of cross-ventilation, its performance must be predicted properly. The CFD technique has been improved and provides rather accurate predictions. However, it is still important to improve ventilation flow rate prediction using a conventional network model, because so many conditions need to be evaluated for effective cross-ventilation and the network model seems to be the most feasible method for some design phases.

Many researchers had demonstrated problems that debase the prediction accuracy of the network model. One of the main problems is that the dynamic pressure of airflow through an inflow opening sometimes does not dissipate and is preserved at an outflow opening (Ishihara 1969, Murakami et al. 1991). Another is that discharge coefficients, which relate wind pressures to ventilation flow rates, vary with wind direction and opening position although they are fixed as constants in the conventional model (Katsuta and Sekine 1961, Vickery and Karakatsanis 1987).

In order to solve the latter problem, Kurabuchi and Ohba et al. (2004) developed a local dynamic similarity model that explains the variation of discharge coefficients, and validated it for inflow openings in their previous studies.

In the present study, two wind tunnel experiments were carried out to investigate the variation of discharge coefficients of outflow openings. The validity of the local dynamic similarity model for outflow openings is discussed on the basis of the results.

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LOCAL DYNAMIC SIMILARITY MODEL (LDSM)

Figure 1 shows the pressures in the vicinity of an inflow opening. It is possible to consider that the pressure field at the inflow opening is represented by three pressures: dynamic pressure normal to the opening \(P_n\), dynamic pressure tangential to the opening \(P_t\) and ventilation driving pressure \(P_r\). The local dynamic similarity model assumes that the \(P_n\), which is directly related to ventilation flow rate \(Q\), is uniquely determined by \(P_t\) and \(P_r\), and that there are dynamic similarities on the relationships among the three pressures when the ratios of \(P_r\) to \(P_t\) are coincident.

As shown in Table 1, the discharge coefficient \(C_d\) and the inflow angle \(\beta\) are described by the ratios of \(P_n\) to \(P_r\) and \(P_t\) to \(P_n\), respectively. If the above assumptions are true, these are uniquely determined by the ratios of \(P_t\) to \(P_r\). Kurabuchi and Ohba et al. (2004) defined the ratio of \(P_r\) to \(P_t\) as dimensionless room pressure \(PR^*\), and verified the model for inflow openings by wind tunnel experiments.

\[
\begin{align*}
P_r &= P_r - P_w \quad \cdots(1) \\
Q &= C_d A \sqrt{\frac{2}{\rho} |P_t|} \quad \cdots(2) \\
C_d &= \frac{P_t}{P_n} \quad \cdots(3) \\
\beta &= \tan^{-1}\left(\frac{P_t}{P_n}\right) \quad \cdots(4) \\
PR^* &= \frac{P_r}{P_t} \quad \cdots(5)
\end{align*}
\]

Figure 2 shows the pressures in the vicinity of an outflow opening. Here, \(P_t\) is defined at the external side of the opening, and static pressure \(P_S\) at the outflow opening is considered to equal the wind pressure \(P_W\), while \(P_S + P_n\) is considered to equal \(P_W\) at the inflow opening.

The discharge coefficient \(C_d\), the outflow angle \(\beta\) and the dimensionless room pressure \(PR^*\) are defined by the same equations as those for the inflow openings. However, \(PR^*\) for the outflow opening is always positive while that for inflow opening is always negative.

\[
\begin{align*}
P_t &= P_t - P_w \quad \cdots(1) \\
Q &= C_d A \sqrt{\frac{2}{\rho} |P_t|} \quad \cdots(2) \\
C_d &= \frac{P_r}{P_n} \quad \cdots(3) \\
\beta &= \tan^{-1}\left(\frac{P_t}{P_n}\right) \quad \cdots(4) \\
PR^* &= \frac{P_r}{P_t} \quad \cdots(5)
\end{align*}
\]

DISCHARGE COEFFICIENT, STATIC PRESSURE AND EXTERNAL AIRFLOW

The first experiment was conducted to reveal the mechanism of the variation of discharge coefficient for an outflow opening.

This experiment was carried out in an Eiffel-type wind tunnel (width: 1200 mm, height: 1000 mm) at
Tokyo Polytechnic University, using a blow-type ventilation model shown in Figure 3. The ventilation model had two rooms, and a round plate was attached around it. A blow fan was connected to the ventilation model to simulate various ventilation flow rates, and a partition with small holes was installed between the two rooms to dissipate the dynamic pressure of the airflow from the fan. The round plate attached to the building had multiple pressure taps to measure the static pressure distribution near the outflow opening. The outflow opening was in contact with the room floor, and the round plate and the room floor were set flush. The model with the round plate was lifted to a height of 250mm from the wind tunnel floor, and the experiment was performed under a uniform approach flow of 7m/s. The incident angle of the approach flow was varied as shown in Figure 4. Under some incident angles, the wind pressure was positive at the opening despite the outflow. However, this situation is possible, e.g. when openings are located in both walls adjacent to a windward corner of a building, or when an opening is located in a roof as well as a windward wall of a building.

In order to observe the discharge coefficient, room pressure was measured at different controlled ventilation flow rates. The room pressure was measured at pressure taps on the ceiling, and the room pressure measured without ventilation \((Q = 0)\) was considered to be wind pressure. Internal/external static pressures on the floor \((P_f)\) and external air velocities around the opening were also measured under different controlled ventilation flow rates. The air velocities were measured with a split film type hot-wire anemometer that discerned 3D velocity vector components.

We defined the discharge coefficient under stagnant conditions as the basic discharge coefficient \((C_{d0})\). The \(C_{d0}\) of the outflow opening used in the experiment was determined to be 0.66 by a pre-experiment without an approach flow.

![Figure 3](image)

**Figure 3** Schematic of first experiment

![Figure 4](image)

**(a) Without wing wall (b) With wing wall**

**Figure 4** Test cases of first experiment

Figure 5 shows the relationships between \(C_d\) and \(P_{o*}\) obtained for all incident angles of the experiment. \(P_i\) to determine \(P_{o*}\) was evaluated from tangential air velocity measured 5mm from the external side of the opening under the no-ventilation condition \((Q = 0)\). As shown Figure 5, the relationships showed two different trends. Where the outflow opening was in a recirculation flow region behind the model, i.e.
90°, 112.5° and 135°. Cd increased gradually by PR* = 5, and was almost constant at the same level of CdS when PR* was greater than 5. Where the outflow opening was not in the recirculation flow region, i.e. 45°, 67.5° and 90° with a wing wall, Cd increased rapidly by PR* = 2, and reached a constant beyond CdS when PR* was greater than 2. There were a few irregular data around PR* = 10 for 135°, which seemed to be due to measurement errors.

Figures 6 and 7 show some results (67.5° and 112.5°) of the internal/external static pressure (Pf) distributions and external airflow patterns around the opening.

From the airflow patterns for both 67.5° and 112.5°, it was found that the course of the airflow diffusing from the opening was narrower when the Cd was smaller. Therefore, it was considered that the decrease of Cd was caused by contraction of the outflow. The contraction of the outflow greatly depended on the strength of the external cross flow. Thus, the local dynamic similarity model reasonably explains the variation of discharge coefficient of the outflow opening.
From the static pressure distributions for 67.5°, a large pressure drop occurred at the leeward side of the opening. This must have been because the external flow along the wall was separated from the wall by colliding with the outflow at the windward side of the opening. It was also found that the course of the outflow was in the region with the pressure drop. Therefore, the static pressure in the course of the outflow was considered to be lower than $P_{w}$. This explains why $C_d$ became greater than $C_{ds}$ as shown in Figure 5. However, the static pressure for 112.5° was not much different from $P_{w}$. This must be because there was originally a large negative pressure downstream of the airflow across the opening, and the airflow across the opening was relatively weak.

The other cases in the recirculation flow region and not in the recirculation flow region showed the same characteristics as for 112.5° and 67.5°, respectively. Thus, the mechanisms that caused the differences in the relationships between $C_d$ and $P_{w}$ were also confirmed for those cases.

**APPLICABILITY OF LDSM TO OUTFLOW OPENINGS**

The second experiment was conducted to investigate the applicability of LDSM to outflow openings under more complicated conditions than the first experiment.

The experiment was carried out in the same wind tunnel as the first experiment, and the same ventilation model without the round plate was used and installed on the floor of the wind tunnel. The approach flow was a boundary layer flow with a power-law index of 0.25, and the reference velocity was kept at 7m/s at the model's upwind edge. The incident angle of the approach flow was varied from 45° to 180°, and the opening position was varied from A to E as shown in Figure 8. $P_{r}$, $P_{w}$, $P_t$, and $Q$ were measured in the same way as in the first experiment. $C_{ds}$ of the outflow opening used in the experiment was determined to be 0.68 by a pre-experiment.

Figure 9(a) shows the relationships between $C_d$ and $P_{w}$ obtained with opening C (center). Under the boundary layer flow condition, the trends were the same as in the uniform approach flow. Increase of $C_d$ to $P_{w}$ was more rapid where the outflow opening was not in a recirculation flow region than where it was in a recirculation flow region. Besides, $C_d$ that was not in a recirculation flow region increased beyond the basic discharge coefficient. However, it was found that the relationships between $C_d$ and $P_{w}$ for 90° and 135° were different. In these cases, there were reattachment points within or very close to the opening area, as shown in Figures 10(b) and (d). Thus, the ventilation airflows were more complicated than for the other cases, and it was difficult to describe this effect by the LDSM.

The directions of the external flow along the wall for 112.5°, 157.5°, and 180° were different. The directions were almost vertical for 157.5° and 180°, while it was more horizontal for 112.5°. However,
there were no substantial differences with directions.

Figures 9(b), (c) and (d) show the relationships between $C_d$ and $P_{Re}^*$ for different opening positions for 67.5°, 90° and 112.5°. The relationships at all opening positions were basically the same as those obtained at opening C (center), and could be distinguished into the two trends mentioned above. There were exceptions for opening A for 67.5° and 90°, and opening B and C for 90°. From Figures 10(a) and (b), they were considered to be due to the separation or reattachment of the external airflow within the opening area.

Figure 9  Relationships between $C_d$ and $P_{Re}^*$ obtained in second experiment

Figure 10  External airflow patterns measured with sealed model (no opening)
DISCUSSIONS

The present experiments have shown that the LDSM reasonably explains the variation of discharge coefficients of outflow openings, which were found to be a function of dimensionless room pressure $P_{R*}$. Thus, the discharge coefficients and ventilation flow rates can be predicted more precisely by the coupled simulation of the network model with the LDSM, if $P_t$ and the relationships between $C_d$ and $P_{R*}$ are known. However, it must be noted that the relationships between $C_d$ and $P_{R*}$ for the outflow openings depended on whether the outflow opening was in the recirculation flow region or not.

The LDSM could not predict the precise $C_d$ where the separation or reattachment point was within or very close to the opening area. Nevertheless, it is considered to be useful even for these cases, because it at least captures the trends of the varying $C_d$.

$P_t$ in this study was determined at a distance of 5mm (1/8 of the opening width) from the external side of the opening. Although the distance was decided provisionally, there were no substantial problems in the present experiments. Further study will investigate whether the 1/8 of the opening width is generally appropriate.

CONCLUSION

The local dynamic similarity model was found to be valid for outflow openings. However, the relationships between $C_d$ and $P_{R*}$ for outflow openings depends on whether the outflow opening is in a recirculation flow region or not. Increase of $C_d$ to $P_{R*}$ is more rapid where the outflow opening is not in a recirculation flow region than where it is. Besides, $C_d$ that is not in a recirculation flow region increases beyond the basic discharge coefficient.

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NOMENCLATURE

- $A$: opening area
- $C_d$: discharge coefficient
- $C_{ds}$: basic discharge coefficient
- $Q$: ventilation flow rate
- $P_r$: static pressure on floor
- $P_{dr}$: dynamic pressure normal to opening
- $P_{drw}$: dynamic pressure of reference velocity ($= \rho U_0^2/2$)
- $P_r$: room pressure
- $P_{vdr}$: ventilation driving pressure ($=P_r-P_w$)
- $P_{R*}$: dimensionless room pressure
- $P_s$: static pressure at opening
- $P_t$: dynamic pressure tangential to opening
- $P_w$: wind pressure
- $U_0$: reference wind velocity at rooftop ($=7\text{m/s}$)
- $\beta$: inflow/outflow angle
- $\rho$: air density

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