EXPERIMENTAL STUDY OF THE DISCHARGE COEFFICIENT OF INTERNAL OPENINGS IN PARTITIONED BUILDINGS

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ABSTRACT
This experimental study uses wind tunnel experiments to investigate the discharge coefficient and flow rate of wind-driven cross ventilation in partitioned buildings. The discharge coefficients of internal openings under different flow conditions were determined by a fan technique. It is found that the internal discharge coefficient is a function of internal porosity, but independent of external porosity and opening location. Based on the experimental results, a predictive model for the internal pressure of multi-room buildings is developed and verified. This model could be used to predict the flow rate through multi-room buildings once the external pressure distribution and opening areas are known.

KEYWORDS: BUILDING VENTILATION, DISCHARGE COEFFICIENT, WIND TUNNEL EXPERIMENT

Introduction

Wind-driven natural ventilation has been demonstrated to be an effective way for maintaining a comfortable and healthy indoor environment [Linden (1999), Santamouris and Wouters (2006)]. The flow rate of wind-driven ventilation is dependent on the external wind conditions, building designs and internal partitions [Etheridge and Sandberg (1996)]. Therefore, a reliable prediction method is important to apply wind-driven ventilation for domestic and commercial buildings.

Predictive models for building ventilation can be divided into two main categories: Computational Fluid Dynamics (CFD) models and multi-zone models. CFD models calculate the air flow inside the building based on the continuity equation and the Navier-Stokes equations [Chang et al. (2003)]. However, Dascalaki et al. (1999) indicated that CFD models are difficult to use for practical design purposes due to the complexity of the modelling procedure and the intricacy in describing real conditions.

On the other hand, multi-zone models compute the flow rate and mass transfer rate between different zones of the building based on the mass conservation and energy balance equation. Several researches used multi-zone models, such as COMIS [Zhao et al. (1998) and Feustel (1999)], CONTAM [Haghighat and Megri (1996)] and POMA [Haghighat et al. (2001)] to simulate air flow rate and indoor air quality in the building, and compare the interzonal air flow rate with the results of CFD models and tracer gas method. Most of these multi-zone models used the orifice equation to calculate flow rate through the internal opening between two rooms:
where $\Delta P_i = P_{i1} - P_{i2}$ is the pressure difference across the internal opening, $\rho_a$ is the air density, $A_i$ is the area of the internal opening, $r_i = A_i/A_w$ is the ratio of area of the internal opening $A_i$ to the area of internal wall $A_w$, $C_{zi}$ is the internal discharge coefficient.

Dascalaki et al. (1999) compared experimental data and calculated results using COMIS, found the discharge coefficient $C_{zi} = 0.65$ for the internal openings. Tan and Glicksman (2005) suggested the internal discharge coefficient $C_{zi} = 0.95$ for small openings. Allard and Santamouris (2006) indicated that the value of $C_{zi}$ is a function of the dimensions of the opening. For small internal openings, a typical value for $C_{zi}$ is 0.65. For large internal openings, $C_{zi}$ has a value close to unity.

Chu et al. (2009), based on wind tunnel experiments, found that the discharge coefficient of external opening is dependent on wind direction, wall porosity and opening Reynolds number. The opening Reynolds number is given by:

$$Re = \frac{u \cdot d}{\nu}$$

where $u = Q/A_w$ is the average velocity at the opening, $d$ is the characteristic diameter of the opening, and $\nu$ is the kinematic viscosity of air.

![Figure 1. Schematic diagram of wind-driven ventilation in a partitioned building.](image)

For buildings that were separated into two rooms by an internal partition as shown in Figure 1. The windward side, leeward side and internal partition each has one opening. The windward opening area is $A_1$, the leeward opening area is $A_2$, and internal opening area is $A_i$. The dimensionless average velocity at the windward opening can be derived from the continuity equation and Eqn. (1):

$$\frac{U_1}{U} = C_{zi} \left[ \frac{\alpha_i^2}{\alpha_1^2 + \alpha_2^2 + \alpha_i^2(1-r_i^2)} \left( C_{pe1} - C_{pe2} \right) \right]^{1/2}$$

where $U$ is the external wind velocity, $C_p$ is the pressure coefficient, $r_i = A_i/A_w$ is the internal wall porosity, subscripts 1 and 2, e and i, represent the windward and leeward sides, the external and internal openings, respectively. Coefficient $\alpha_i = A_{r1} \cdot C_{zr1}$, $\alpha_2 = A_{r2} \cdot C_{zr2}$, where $C_{zr}$ are the ratios of discharge coefficients:

$$C_{zr1} = \frac{C_{zi}}{C_{zi}}$$

$$C_{zr2} = \frac{C_{zi}}{C_{zi}}$$

Ratios of opening areas are defined as:
\[ A_{r1} = \frac{A_1}{A_i} \quad A_{r2} = \frac{A_2}{A_i} \]  

(5)

The dimensionless average velocity at the internal opening is:

\[ \frac{u_i}{U} = C_{z_i} \left[ \frac{\alpha_1^2 \alpha_2^2 (1 - r_i^2)}{\alpha_1^2 + \alpha_2^2 + \alpha_1^2 \alpha_2^2 (1 - r_i^2)} \right] \left[ C_{p_e1} - C_{p_e2} \right] \]  

(6)

Based on Eqns (1) and (3), it can be shown that the internal pressure coefficient of room 1 equals to:

\[ C_{p_i1} = C_{p_e1} - \frac{\alpha_2^2 (C_{p_e1} - C_{p_e2})}{\alpha_1^2 + \alpha_2^2 + \alpha_1^2 \alpha_2^2 (1 - r_i^2)} \]  

(7)

and internal pressure coefficient of room 2 equals to:

\[ C_{p_i2} = C_{p_e2} + \frac{\alpha_1^2 (C_{p_e1} - C_{p_e2})}{\alpha_1^2 + \alpha_2^2 + \alpha_1^2 \alpha_2^2 (1 - r_i^2)} \]  

(8)

The equations shown above can be used to predict the internal pressure coefficients \( C_{p_i1}, \) \( C_{p_i2} \) and inlet velocity \( \frac{u_i}{U} \) once the external pressure coefficients \( C_{p_e1} \) and \( C_{p_e2}, \) discharge coefficients \( C_{z1} \) and \( C_{z2} \) and the internal porosity \( r_i \) are known.

Based on the studies cited above, there is a need to elucidate the relationship between the internal discharge coefficient and opening size, partition configuration. This study used wind tunnel experiments systematically investigate the influences of external wind speed, opening size and partition configuration on the internal flow rate and the discharge coefficient. The discharge coefficients of various flow conditions were determined by a fan technique. The experimental results will also be used to verify the above model.

**Experimental Setup**

The experiments were carried out in an open-circuit, blowing-type wind tunnel. The total length of the wind tunnel was 8.3 m, the test section of wind tunnel was 1.2 m wide and 0.6 m high, and the wooden platform was 1.80 m long, 1.20 m wide. The schematic diagram of the experimental setup is shown in Figure 2.
A cubic model with external dimensions: width and height $H = 0.40$ m, was mounted on the centerline of the platform. The distance from the beginning of the test section to the model was 1.25 m. The surfaces of the model were made of smooth acrylic plate (thickness $4.8$ mm) with square-shaped opening (diameter $d = 40, 60$ and $100$ mm) at the center of the plate. The space inside the model was evenly separated into two zones by an internal partition plate. The plate was also made of acrylic with square-shaped opening (diameter $d_i = 20, 30, 40, 50, 60, 80$ and $100$ mm) at three different locations (center, edge and corner).

The external and internal pressures were measured by a multi-channel high-speed pressure scanner (ZOC33/64PX, Scanivalve Inc.). The measuring range of the pressure sensor was $\pm 2758$ Pa, with a resolution of $\pm 2.2$ Pa. The sampling frequency was $100$ Hz, and the sampling duration was $163.84$ sec. The pressures were measured as pressure differences from the reference static pressure near the inlet of the test-section. The windward side pressure distribution was found to be unaffected by the size of the opening.

The fan technique described by Chiu and Ethridge (2007) was adopted in this study in order to determine the internal discharge coefficients of different flow conditions. The flow rate can be controlled by a fan, and the resulting pressure difference across an opening can then be measured. The mean flow rate, $Q$, was measured by a nozzle meter. When the fan technique was used, a porous plate ($150$ mm x $150$ mm) was installed inside the model in order to alleviate the effects of suction and blowing on the flow field inside the model.

For cross ventilation, the locations of windward and leeward openings were at the center of the wall. But there are three different configurations for the internal opening in this study: (1) Case 1: internal opening at the center of the partition wall; (2) Case 2: internal opening at the edge of the partition wall; (3) Case 3: internal opening at the corner of the partition wall. The wind direction is defined as the incidence angle of the approaching flow; the windward facade was normal to the wind when wind direction $\theta = 0^\circ$.

**Results and Discussion**

This section describes the experimental results of the internal discharge coefficients $C_{zi}$ of different flow conditions. The range of Reynolds number is $5,000 \sim 40,000$, which is close to the typical value of Reynolds number for real buildings. In this part of the experiment, the leeward opening was connected to a porous plate, a nozzle meter and a fan. The external wind speed $U = 17.5$ m/s, and wind direction $\theta = 0^\circ$, for all the cases.

Figure 3 illustrates the relationship between the internal discharge coefficient $C_{zi}$ and Reynolds number for different opening configurations (Case 1 ~ 3). External windward porosity $r_1 = A_1/A_w = 6.25\%$ (opening $d_1 = 100$ mm). It can be seen that the internal discharge coefficients are independent of Reynolds number and opening configurations except for the flow condition: $r_1 = 6.25\%$ in Case 1. The average value of $C_{zi} = 0.94$ when $r_1 = 1.0\%$ ($d_i = 40$ mm) for all three different opening configurations (Case 1 ~ 3) was very close to the value of $0.95$ suggested by Tan and Glicksman (2005) for small internal openings. In addition, the value $C_{zi} = 0.69$, when $r_1 = 2.25\%$ ($d_i = 60$ mm) and $C_{zi} = 0.63$ when $r_1 = 6.25\%$ ($d_i = 100$ mm) were close to $0.65$ suggested by Dascalaki et al. (1999) for internal door. These results demonstrated that the internal discharge coefficient is a function of the opening size.

Figure 4 shows the relationship between internal discharge coefficient and Reynolds number for different internal porosities. External porosity $r_1 = 6.25\%$, opening configuration Case 3. The internal discharge coefficient $C_{zi} > 1$ when internal porosity $r_i < 1.0\%$. This is due to the orifice equation cannot be used to calculate the internal flow rate when the internal porosity $r_i < 1.0\%$. 
Figure 3. Internal discharge coefficients as a function of Reynolds number for different opening configurations. External porosity $r_1 = 6.25\%$. (a) internal porosity $r_i = 1.0\%$; (b) internal porosity $r_i = 2.25\%$; (c) internal porosity $r_i = 6.25\%$. 
Figure 4. Internal discharge coefficients as a function of Reynolds number for different internal porosities. External porosity $r_1 = 6.25\%$, opening configuration is Case 3.

Figure 5 plots the internal discharge coefficient $C_{zi}$ as a function of the internal porosity $r_i$. The internal discharge coefficient $C_{zi}$ decreased as the internal porosity $r_i$ increased, and the decrease rate slowed down when $r_i > 4.0\%$ and reach a constant value $C_{zi} = 0.60$. Based on the results of $r_i = 1.0\%$ ~ $6.25\%$, an empirical relation between $C_{zi}$ and $r_i$ can be found:

$$C_{zi} = \frac{0.601r_i}{r_i - 0.00355}$$

Figure 5. Relationship between internal discharge coefficient and internal porosity $r_i$.

This section discusses the experimental results of wind-driven cross ventilation through partitioned building. The windward and leeward wall each has one opening at the center. The internal opening at three different locations: (1) at the center of the partition wall; (2) at the edge of the partition wall; (3) at the corner of the partition wall. In this part of the
experiment, the fan, porous plate, and nozzle meter were not used. The external wind speed \( U = 17.5 \text{ m/s} \) and wind direction \( \theta = 0^\circ \), for all the cases.

![Graph showing internal pressure coefficient as a function of opening ratio](image)

**Figure 6.** Internal pressure coefficient of room 1 as a function of opening ratio \( A_2/A_1 \) for different cases. Internal porosity \( r_i = 6.25\% \).

The internal pressure coefficient \( C_{pi1} \) is plotted as a function of opening ratio \( A_2/A_1 \) for different partition configurations in Figure 6. The symbols are the measured internal pressure coefficients, and the lines are the predictions of Eqn. (7). The internal pressure coefficient \( C_{pi1} \) is close to windward pressure coefficient \( C_{pe1} \) when \( A_2/A_1 \ll 1.0 \); whereas when \( A_2/A_1 \gg 1.0 \), the internal pressure coefficient \( C_{pi1} \) was close to leeward pressure coefficient \( C_{pe2} \). The agreement between predicted and measured pressure coefficients demonstrated that Eqns. (7) could be used to predict the internal pressure coefficient of partitioned buildings.

Dimensionless inlet velocity at the windward opening \( u_1/U \) is plotted as a function of opening ratio \( A_2/A_1 \) for different cases in Figure 7. The symbols are the measured velocities at the windward opening, and the lines are the predictions of Eqn. (3). The good agreement between the measured and predicted inlet velocities demonstrated that Eqn. (3) can be used to predict the flow rate in partitioned buildings.

**Conclusions**

This experimental study examines the applicability of orifice equation for partitioned buildings. The values of internal discharge coefficient for different opening sizes and flow conditions were measured by a fan technique. It was found that the internal discharge coefficients were dependent on the internal porosity, but independent of external porosity and opening configuration. The relationship between the internal discharge coefficient and internal porosity was then used to calculate the internal pressure coefficients and average inlet velocity for three different opening configurations: internal opening at the center of partition wall; internal opening at the edge of partition wall; internal opening at the corner of partition wall. The agreement between predicted and measured internal pressure coefficients demonstrated that the orifice equation can be used to predict internal pressure and flow rate through building openings.
Figure 7. Dimensionless velocity at the windward opening plotted as a function of opening ratio $A_2/A_1$ for different cases. Internal porosity $r_i = 6.25\%$.

References


