A REVIEW OF THE CONCEPT OF DISCHARGE COEFFICIENT FOR DESIGNING NATURAL VENTILATION IN BUILDINGS

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ABSTRACT
The need for improving energy efficiency and air quality in buildings has promoted the revival of natural ventilation in various types of buildings in the last 20 years. There is a practical need for improving design accuracy of natural ventilation. Accurate specification of discharge coefficient is essential for providing accurate engineering design. We have reviewed literature on the concept of discharge coefficient and provided a summary of the existing studies. We have summarized how the discharge coefficient is affected by aspect ratio of the opening, opening degree, and the pressure difference and the temperature difference across the opening etc. Considering the current status and the applications of natural ventilation in China, characteristics of airflow from the opening with screen were discussed.

INDEX TERMS
Discharge coefficient, Aspect ratio, Opening degree, Pressure and temperature difference, Screen

INTRODUCTION
In recent years, natural ventilation has become popular. Natural ventilation can be defined as fresh air supplied through openings in the building’s envelope without electricity consumption (Bjørn et al. 2000). Natural forces such as buoyancy and wind drive natural ventilation in buildings. The air flow of natural ventilation depends on the building’s characteristic parameters as well as on the external ambient conditions. The resistance of the opening, which is commonly characterized by the discharge coefficient of the ventilation system, is an important factor that affects the flow of natural ventilation. In the absence of better information, a generally used value for the discharge coefficient of a sharp-rimmed large opening is \( C_d = 0.6 \pm 0.1 \) (Flourentzou et al. 1998). It is usually regarded as a constant value in the analysis, engineering design or numerical simulation of natural ventilation.

As the complexity of the flow of natural ventilation, the discharge coefficient is related to many factors. Without a clear idea about it and regarding it as a constant may result in incorrect prediction of natural ventilation flow rates or incorrect sizing of ventilation openings.

In order to improve our knowledge of the discharge coefficient, and to describe air flows in buildings more correctly, this paper addressed the basic principle of the discharge coefficient, summarized the factors related with it that include opening strategies, pressure difference and temperature difference across the opening. Finally, the paper analyzed the characteristics of airflow from the opening with screen which have been popularly applied in building openings in China.

THE MEANING OF THE DISCHARGE COEFFICIENT
The discharge coefficient quantifies the air flow efficiency of an opening or alternatively the air flow resistance of an opening. Many of the discharge coefficient values used are derived from data traditionally used for fluid flow in pipes. The value of 0.6 also can be found from the manual of hydraulics (Idelchik 1994).

According to the Bernoulli model, the volumetric flow rate through a window is defined by the pressure drop across the window, together with the geometrical opening area (Andersen 1996).

Generally, the volume flow rate through the opening can be calculated by Eq.(1).

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\[ Q = c_d A \left[ \frac{2\Delta p}{\rho_0} \right] \]
\[ C_d = \varepsilon \Phi \]  

Where \( \varepsilon \) is jet contraction coefficients, \( \Phi \) is velocity coefficients, which is equal to \( \frac{1}{\sqrt{\zeta}} \), \( \zeta \) is the loss coefficients of the opening. Flourentzon et al. (1998) performed experimental studies in a naturally ventilated building to determine flow coefficients. The velocity coefficients \( \Phi = 0.7 \pm 0.1 \) and jet contraction coefficients \( \varepsilon = 0.85 \pm 1 \) found in the experiment were in agreement with the generally accepted value of the discharge coefficient \( C_d = \varepsilon \Phi = 0.6 \pm 0.1 \).

FACTORS AFFECTING THE DISCHARGE COEFFICIENT OF THE OPENING

In natural ventilation systems, fresh air is often provided through opening of windows. Different window shape and different opening angle affect thermal comfort conditions in the occupied zone. For different opening strategies, should the value of discharge coefficient be still kept as 0.6?

ASPECT RATIO

Bot (1983) presented an empirical equation that related discharge coefficient of rectangular openings to the aspect ratio \( L/H \), the ratio between the length and the width of the opening.

\[ C_d = 1/\sqrt{1.75 + 0.7 \exp[-(L/(32.5H))] \]  

It is seen in Figure 1 that the discharge coefficient is almost linearly proportional to the aspect ratio, which shows that the discharge coefficient can be increased by increasing the aspect ration.

![Figure 1. The relation of \( C_d \) with the aspect ratio](image)

OPENING DEGREE

Many building openings can be controlled by occupants, for example, the side hung window or the door. Their opening areas can be changed by varying the angle of opening and then the loss coefficients will alter. It is known that the loss coefficients of openings will be decreased by increasing the opening angle from the hydrodynamics principle, in the result that the discharge coefficient will be increased.

Liu (2000) measured the flow coefficient of the typical doors and windows in a high-rise experimental fire tower. The results are summarized in table (The discharge coefficient in the degree of 0 corresponds to the aperture area of the door).
Table 1. The discharge coefficient of the window and the door (Liu, 2000)

<table>
<thead>
<tr>
<th>The opening degree</th>
<th>90°</th>
<th>45°</th>
<th>0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single door</td>
<td>0.34</td>
<td>0.75</td>
<td>0.45</td>
</tr>
<tr>
<td>Double doors</td>
<td>0.31</td>
<td>0.78</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The results of the experiment reveal that the discharge coefficient of the opening can be very different for different opening angles. The largest discharge coefficient occurs when the opening angle is 45°. The use of a constant value in natural ventilation design can be very misleading. For example, if a value of 0.6 is used, the air flow rate for a double door at 90° can be over-predicted by nearly 100%. This can have significant implications in smoke control related calculations.

PRESSURE AND TEMPERATURE DIFFERENCE

In order to analyze the discharge coefficient, Bjørn (2000) and Heiselberg (2001) carried out a series of laboratory measurements to determine the characteristics of airflow from open window. Their experiment results are shown in Fig. 2 and Fig. 3.

Fig. 2 shows the discharge coefficient as a function of the pressure difference across the opening for different opening areas for two window types. Especially in the case of the side hung window, the value of the discharge coefficient varies significantly at small pressure differences across the opening, while it becomes constant at large pressure differences. This indicates a Reynolds number dependency that might be important to take into consideration as natural ventilation systems often operate at very small pressure differences (Heiselberg 2001).

Fig. 2 also shows that the absolute value of the discharge coefficient at small opening angles above 1. This might be caused by incorrect estimation of the geometrical opening area and exfiltration in the experiments.

![Figure 2. C_d, for side and bottom hung windows as a function of pressure difference for different opening areas (Heiselberg, 2001)](image-url)

Fig. 3 shows the discharge coefficient for the side hung window as a function of Ar'. Ar' expresses the influence of the buoyancy, and is defined by Heiselberg (2001).
Where $T_{oc}$ is air temperature in the occupied zone [K], $T_0$ is temperature of inlet air [K], $Q$ is the volume rate of flow through the opening [m$^3$/s].

In a situation with both a temperature and a pressure difference across the opening, the discharge coefficient can be described as a function of $Ar'$ and the opening area, and the value of the discharge coefficient is considerably reduced at large temperature differences. For small opening areas the dependency is not so strong. For the bottom hung window the discharge coefficient showed a very small dependency on temperature difference.

Heiselberg (2001) also studied the characteristics of airflow of different types of windows. Obviously it is difficult to characterize the discharge coefficients as related to different types of windows, in particular if the experiments were carried out under different test conditions.

SCREEN
A screen is commonly used in various types of buildings. Typically, in domestic buildings, screens are used for preventing the entrance of birds and insects.

A number of authors have worked on the flow through screen (Bailey 1981, Nijskens et al. 1985). These characteristics are generally evaluated in empirical terms of “permeability” or “coefficient of discharge”.

In the steady-state flow of an incompressible fluid through a highly porous material, the motion equation for one-dimensional steady-state flow through a permeable material can be reduced to the Forchheimer equation (Miguel 1997). Miguel (1997) considered that Forchheimer equation was valid for flow through screen, when the Reynolds number (based on pore size) was less than 100–150. In this flow regime, inertial forces do not dominate and so viscous forces cannot be neglected. But when Reynolds number is large than 150, viscous forces can be neglected, the integration of Forchheimer equation yields the well-known Bernoulli equation, and the pressure difference across the window can be expressed by the discharge coefficient:

$$ \Delta P = \frac{1}{2} \frac{\rho}{C_d^2} u^2 $$

For the insect screen used in the domestic building, the mesh size $d=2\text{mm}$, and the velocity of wind is 1.69m/s, the kinetic viscosity of air in room temperature is $15.7\times10^{-6}\text{m}^2/\text{s}$. The Reynolds number (Re=$ud/\nu$) for the typical insect screen is 215. So we can conclude that the flow through insect screen in the natural ventilation can be described by Eq.(5) and the viscous forces can be neglected. When the screen size is small, in other words, the Reynolds number
smaller than 150, Bailey (2003) analyzed the flow in detail. The pressure difference across the opening with a screen was predicted by combining the separate flow resistances of the opening and of the screen. The discharge coefficient was found to be dependent on Reynolds number (based on fibre thickness) and screen porosity.

CONCLUSIONS
The discharge coefficient increase with the increase of the aspect ration, the angle of opening.

The discharge coefficient of the same window also varies at small pressure differences across the opening, while it becomes constant at large pressure differences. It is considerably reduced at large temperature differences.

The flow through insect screen in the natural ventilation can be described by the discharge coefficient, however the actual value need to be decided by further experiment and analysis.

From above analysis, it is concluded that the discharge coefficient for an opening cannot be regarded as a constant as it varies considerably both with the aspect ratio, the opening degree and the pressure and temperature difference. More experimental data is required, especially with regard to different type of the opening. Further study will be carried out in Hunan University. We hope to obtain more experimental data about the discharge coefficient and the database can be used for the actual design of the natural ventilation.

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REFERENCES