CALCULATION OF DISCHARGE COEFFICIENT IN COMPLEX OPENING (LAMINAR FLOW)

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ABSTRACT

The efficient of natural ventilation for energy saving in building depends not only on the appropriate position and orientation of building opening but also the configuration of opening itself. Different air flow characteristics could be obtained depend on each type of the opening. Therefore database development on the discharge coefficient for different types of opening especially for complex opening is vital.

This research carries on the forth going research done by Nattavut et al. [1-2] in calculating the discharge coefficient in complex opening by adding more types of complex opening as well as more air flow directions to the opening. The discharge coefficient equations obtained by Nattavut et al. [1-2] are then modified to gain more accuracy and can be used for various types of opening. The initial air flow is set to be laminar and developed until it is fully developed in the test equipment. Two characteristics of discharge coefficient distribution with respect to the air flow direction for different types of opening are found. One is the bell type distribution and the other is the M type distribution. Moreover it is found also that number of internal opening varies inversely with discharge coefficient. Shape factor is applied for identifying different types of complex opening. The mathematical model is set up to determine equations for calculating discharge coefficient. Equations received are accurate with coefficient of determination equal to 0.90195 for vertical opening and 0.9098 for horizontal opening.

1. INTRODUCTION

Natural ventilation is one of several methods in performing energy saving for high rise buildings in which major portion of energy consumption is in the air conditioning system. However, to maximize the utilization of natural ventilation requires important parameters such as proper building orientation to suite weather conditions such as wind and solar direction through the year. Opening configuration as well as its location on the building is also important in order to achieve the uniform air stream throughout the building. Both architects and engineers must work together to achieve both functional and efficient building. A precise calculation of air flow rate through the opening is essential. However there are very few data for discharge coefficient available at present for that purpose. This leaves a few choices for architects in configuring building openings. Nattavut et al. [1-2] performed an experiment

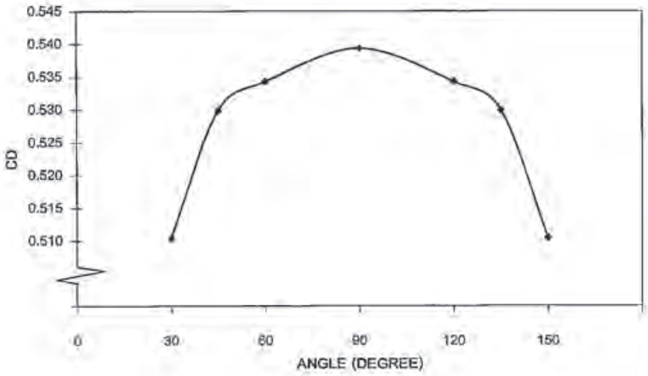

Figure 1 Bell shape distribution of discharge coefficient, [1-2]

to determine discharge coefficient for 32 opening configurations in various air flow directions. The shape factor was used to classify different opening configurations for mathematical purpose in order to establish equations to determine the discharge coefficient through opening. The rectangular, square and circular openings were used along with the air flow direction varied from 30 to 90 degree. Plotting between the discharge coefficient and the air flow direction indicated that the discharge coefficient is changed rapidly when the air flow direction is 30 degree and lower as shown in figure 1 and 2.

This rapid change in discharge coefficient resulted in the inaccuracy of equations obtained and hence not appropriate to be used at low air flow direction. Therefore in this research, the experiment was done to obtain more data for the range of 30 degree and below in order to set up new equations that can be applied for the whole range of air flow direction as well as to gain more accuracy.

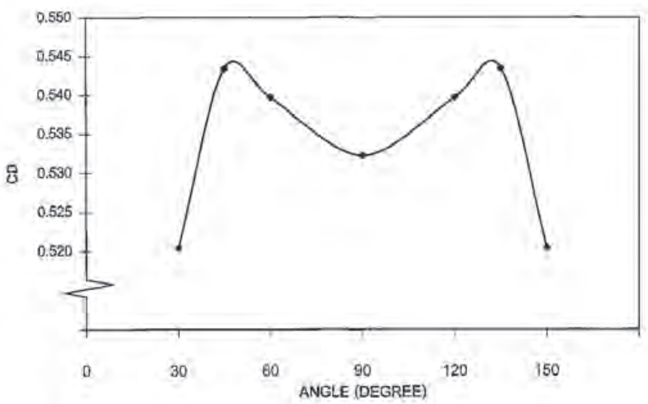

Figure 2 M shape distribution of discharge coefficient, [1-2]

2. RELATED THEORY

Natural ventilation is the air flow which is determined by wind direction and temperature through building openings under various ambient conditions. It can be controlled by the operation of building openings to provide the proper condition for the building in order to achieve the following objectives;

a. To maintain indoor air condition of the building.
b. To enhance the thermal comfort condition of the building.
c. To prevent building structure from heat by carrying heat out from the structure so that building structure is always in the cool and dry condition.

2.1 PARAMETERS RELATED TO THE NATURAL VENTILATION

Air is used as a media in transferring heat from the building via convection process. The amount of heat transfer depends on relation among specific heat of the air, air flow rate and temperature different between inside and outside of the building. Figure 3 shows different natural air flows through different location of building openings. For this study, we considered the air flow through the building opening as the air flow through an orifice inside the tube as shown in figure 4.

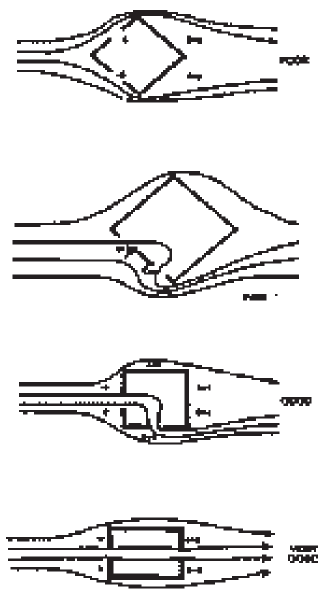

Figure 3 Natural air flows through the building.

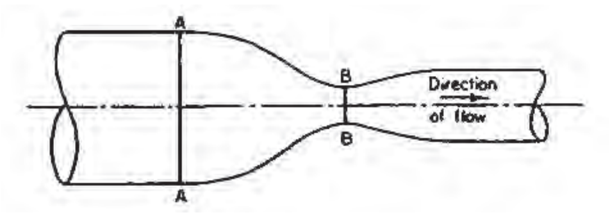

Figure 4 *Air flow through an orifice inside the tube*

Assumptions used in the experiment were as follow;

a. One dimension and steady flow
b. Streamline flow
c. Frictionless flow
d. Uniform velocity at AA and BB section
e. Uniform pressure at AA and BB section
f. Same height at AA and BB when referred to the reference datum

Let

P_1, P_2 = Absolute pressure at AA and BB
V_1, V_2 = Average velocity at AA and BB
ρ_1, ρ_2 = Air density at AA and BB
A_1, A_2 = Cross section area at AA และ BB
Ratio A = A_1/A_2

The different between P_1 and P_2 depends on ratio A. However the value of P_2/P_1 approaches to one. Therefore using Bernoulli's principle and continuity equation, the theoretical air flow rate equation is

$$Q_t = A_2 \sqrt{\frac{2 (P_1 - P_2)}{p (1 - A^2)}} \qquad (1)$$

In practice, the actual air flow rate (Qa) is always less than the theoretical air flow rate (Qt) and the ratio between the actual flow rate and the theoretical air flow rate is called the discharge coefficient, CD. This term is used to indicate how efficient it is for the air to enter the opening.

$$C_D = \frac{Q_a}{Q_t} \qquad (2)$$

2.2 AIR FLOW MEASUREMENT USING ORIFICE

In this experiment, orifice was used to measure the air flow rate. The appropriate orifice thickness should be less that those specified in table 1 when temperature of the air in the tube is less than 315oC [5], [8]

Table 1 Orifice thickness

Tube size	Orifice thickness, inch
3” below	3/32 ± 1/32
4”- 6”	5/32 ± 1/32
7”- 8”	1/4 ± 1/16
10” up	3/8 ± 1/8

3. EXPERIMENT

The test equipment used for this research consists of a long plastic tube with square cross section. The cross section dimension is 15x15 cm. (Figure 5). The long plastic tube is divided into 3 sections. The first section is the entrance section. The second section is the test section (for changing the opening orientation). This section has flange that is inclined for 15, 30, 45, 60, and 90 degree to the air flow direction. The last section is the exit section that connected with the velocity measuring device and the exhaust blower. The flow straightener is installed at the entrance section in order to obtain uniform and laminar air flow in the long and straight tube. This enables the flow to be fully developed before entering into the test section.

Fourteen openings are used in the experiment. They are as follow;

a. Eight rectangular openings with different rectangular subdivisions inside each opening.
b. Six rectangular openings with different triangular subdivisions inside each opening.

Openings and their shape factors are shown is Figure 6.

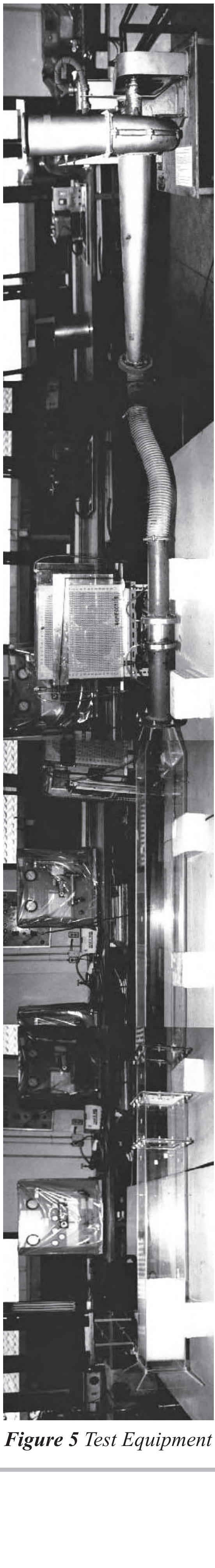
Figure 5 *Test Equipment*

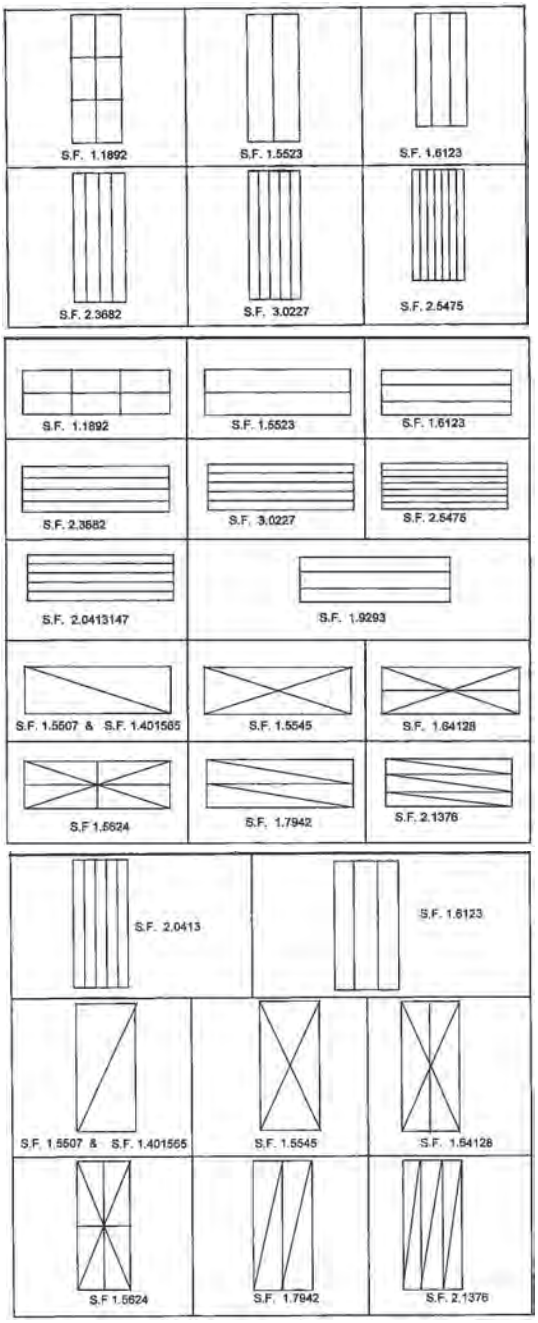

Figure 6 *Openings and their shape factors*

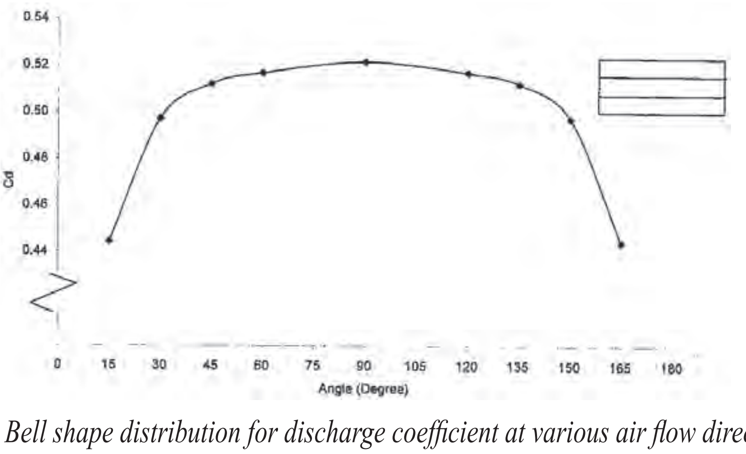

Figure 7 *Bell shape distribution for discharge coefficient at various air flow directions*

The test procedure is as follow;

a. Changing of the opening shape.
b. Changing the orientation of opening with respect to air flow direction at 15, 30, 45, 60, and 90 degree.
c. Measuring the pressure drop across the test section and the velocity measuring device.
d. Calculate the air flow discharge coefficient.

4. RESULT ANALYSIS

Results from the experiment can be analyzed as follow;

a. The distribution of discharge coefficient with respect to air flow direction can be classified into 2 characteristics;
   - Bell shape distribution characteristic for rectangular openings that placed horizontally. (Figure 7)
   - M shape distribution characteristic for rectangular shape openings that placed vertically. (Figure 8)

It can be seen that for M shape distribution, the maximum discharge coefficient occurs at 45 and 135 degree. For bell shape distribution, the maximum discharge coefficient occurs at 90 degree and the distribution is flat over the wide range of air flow direction. Therefore to obtain maximum air flow rate, the horizontal opening should be placed in the perpendicular direction to the air flow direction while for the vertical opening, it should be placed either 45 or 135 degree to the air flow direction.

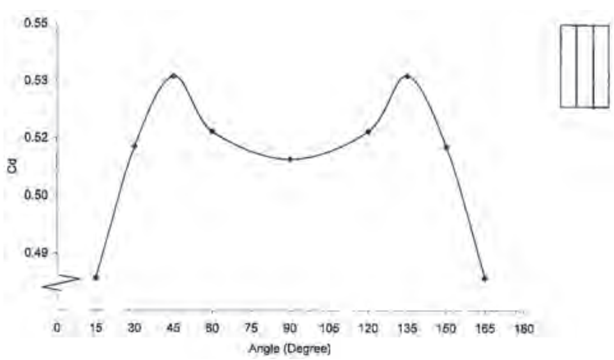

Figure 8 *M shape distribution for discharge coefficient at various air flow directions*

b. For opening with the same shape but has different no. of subdivision, it is found that the discharge coefficient is lower as the number of subdivision increase (Figure 9-10).
c. For opening with the same shape and the same number of subdivision but has different subdivision shapes which can be mathematically represented by the shape factor, i.e.,

$$S.F. = \frac{\text{Actual perimeter of the cross section}}{\text{Perimeter of the equivalent circle}} \quad (3)$$

$$\text{S.F.} = \frac{SF_1 + SF_2 + SF_3 + \ldots\ldots + SF_{n-1} + SF_n}{n} \quad (4)$$

It is found that opening with low shape factor provides higher discharge coefficient than the opening with high shape factor (Figure 11-12).

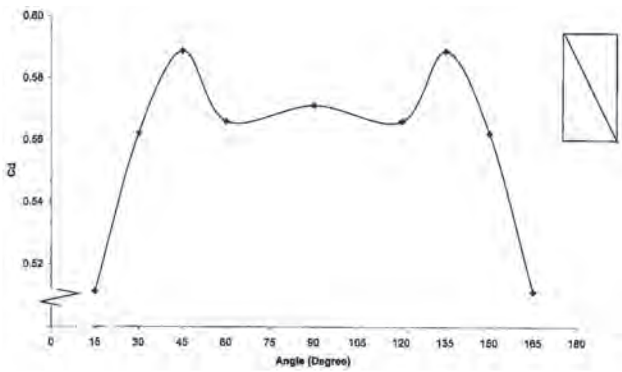

Figure 9 *Discharge coefficient of opening with 2 subdivisions inside the opening*

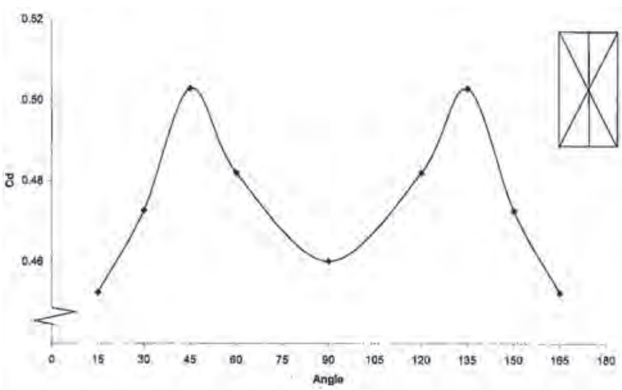

Figure 10 *Discharge coefficient of opening with 6 subdivisions inside the opening*

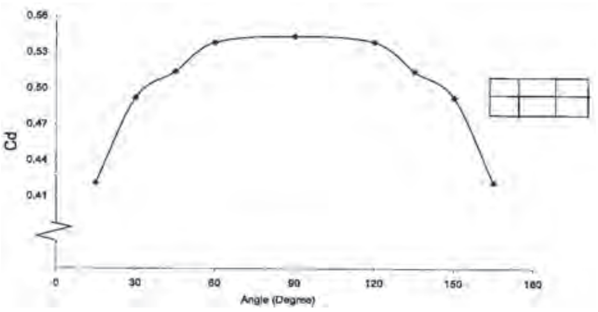

***Figure 11** Discharge coefficient of opening with shape factor = 1.189233*

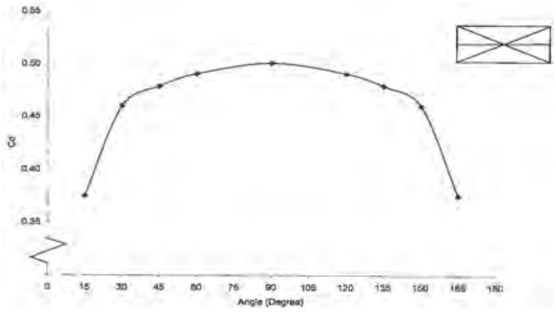

***Figure 12** Discharge coefficient of opening with shape factor = 1.64128*

d. From 30 to 15 degree, the discharge coefficient trends to change rapidly to a small value.

5. EQUATION AND VERIFICATION

Data received from this experiment was then combined with data received from Nattavut et al. [1-2] in order to increase the database for developing equations used for calculating the discharge coefficient. The parameters that affect the discharge coefficient are as follow;

a. Placement of the opening
b. Shape factor of the opening
c. No. of subdivision inside the opening
d. Orientation of the opening with respect to air flow direction

Due to opening placement that affects the discharge coefficient distribution as mentioned before, two equations for calculating discharge coefficient were derived, i.e., one for horizontal opening placement and the other for vertical opening placement. Each equation depends on parameters such as shape factor, no. of subdivision and orientation of the opening. Regression analysis was applied to data obtained from the experiment. The equations obtained were as follow;

a. Equation for bell shape distribution

From data received in this experiment;

$$C_D = e^{-0.03656(SF^{1.3}N^{0.75})\sin\left(\begin{matrix}1.938A^5 - 8.3253A^4 + 13.555A^3\\ -10.552A^2 + 4.0412A\end{matrix}\right)} \quad (5)$$

From combined data;

$$C_D = e^{-0.0315(SF^{1.2}N^{0.8})\sin\left(\begin{matrix}1.677A^5 - 7.3982A^4 + 12.39A^3\\ -9.9032A^2 + 3.8595A\end{matrix}\right)} \quad (6)$$

b. Equation for M shape distribution

From data received in this experiment;

$$C_D = e^{-0.02494(SF^{1.4}N^{0.9})\sin\left(\begin{matrix}3.7421A^5 - 14.936A^4 + 22.027A^3\\ -15.199A^2 + 5.0486A\end{matrix}\right)} \quad (7)$$

From combined data;

$$C_D = e^{-0.02115(SF^{1.25}N^{0.95})\sin\left(\begin{matrix}4.4662A^5 - 17.682A^4 + 25.571A^3\\ -16.911A^2 + 5.2013A\end{matrix}\right)} \quad (8)$$

where

C_D = Calculated discharge coefficient
A = Angle of the opening with respect to air flow direction, radian, $0 \le A \le \pi/2$
N = No. of subdivision inside the opening
SF = Average shape factor of opening

Eq. (5), (6), (7) and (8) were statistically tested with the discharge coefficient values received from the experiment to determine the accuracy of the equations developed. The results are as follow;

Equation (5):
Coefficient of Determination, $r^2 = 0.917023$
Average of Percent Error = 3.41%

Equation (6):
Coefficient of Determination, $r^2 = 0.9098$
Average of Percent Error = 3.57%

Equation (7):
Coefficient of Determination, $r^2 = 0.948119$
Average of Percent Error = 3.17%

Equation (8):
Coefficient of Determination, $r^2 = 0.90195$
Average of Percent Error = 3.22%

From Eq. (5), (6), (7) and (8), the opening angle with respect to the air flow direction is specified in the range from 0 to $\pi/2$ (0 to 90 degree). However, due to the symmetry of the discharge coefficient distribution, these equations can also be used for the range 0 to π (0 to 180 degree) by using 60, 45, 30, 15 degree as representatives for 120, 135, 150 and 165 degree respectively for the calculation.

6. CONCULSION

From results obtained, conclusions can be drawn as follow;

a. Opening with high shape factor provides low discharge coefficient. However, the change of shape factor at high shape factor has a slightly effect to the discharge coefficient when compared with the low shape factor at every air flow direction. Therefore selecting the opening with low shape factor or in other word the opening with small no. of subdivision inside the opening results in high efficiency ventilation.

b. Positioning the horizontal opening perpendicular to the air flow direction provides maximum ventilation. For vertical opening, positioning the opening at 45 or 135 degree provides maximum ventilation.

Data received from this research when combined with data received from Nattavut et al. [1-2] provides equations for determining the discharge coefficient at the wider range of air flow direction with higher accuracy at small air flow direction. This enables more accuracy in natural ventilation simulation for the building with openings.

7. REFERENCES

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