Investigation of discharge coefficient of louvre openings in naturally ventilated buildings

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Abstract. Louvre openings are widely used for ventilation in residences at tropical regions. Traditional households rely primarily on natural ventilation for cooling instead of using air conditioners throughout the year. Hence, a design strategy that maximizes the natural ventilation rate with an accurate discharge coefficient is necessary. The discharge coefficient for a traditional window without a louvre is 0.6. However, studies on discharge coefficients for louvre openings with sashes are lacking. Discharge coefficient will differ according to the installed sash owing to increased contraction and friction losses. Therefore, we determined the discharge coefficient value for various sash angles and the impact of the louvre geometric parameter on the discharge coefficient. To investigate the effects of geometry on the discharge coefficient, real-time natural ventilation rate was quantified using the tracer gas (constant concentration) method. Pressure difference, outdoor wind velocity, and temperature difference were also measured. The opening types were divided into three cases: louvres with a sash angle of 0°, 15°, and 30° with similar opening areas. The results show that discharge coefficients for louvres with sash angles of 0°, 15°, and 30° are 0.80, 0.62, and 0.41, respectively, indicating that the coefficient decreases with increasing sash opening angle.

1 Introduction

Natural ventilation (NV) benefits the environment by lowering operating costs, improving indoor air quality (IAQ), and increasing occupant satisfaction with their thermal comfort [1, 2]. In addition, NV can provide adequate ventilation [3, 4]. However, accurately determining the ventilation rate of a naturally ventilated building remains a challenge [5, 6]. It is crucial in building design to control ventilation openings and monitoring gas and dust emissions from NV housing [7].

Natural ventilation has been investigated in buildings for more than 50 years. Despite many descriptive experimental and numerical studies conducted for airflow estimation paired with heat transfer to aid such an understanding, the mechanics of such a physical problem remains unclear. Many factors influence the proper implementation of natural ventilation systems to meet the comfort needs of occupants, thereby affecting a building’s energy usage. Natural ventilation has attracted interest because of its vent and cooling benefits. Such benefits can significantly reduce building energy consumption with respect to location (latitude). In tropical latitudes with high humidity and temperatures with weak day-night fluctuations, ventilation, appropriate thermal mass, and insulation significantly improve thermal comfort[8, 9]. This is particularly true for vernacular houses in tropical regions. In tropical regions, households mainly rely on natural ventilation for cooling, rather than operating an air conditioner for the entire year. In addition, louvre opening

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are always higher than 0.82, and the pressure difference for the natural ventilation process is often below 10 Pa.

In addition, Chiu et al. [14] discovered a relationship between the Cd value and external wind activity, in which values as low as 0.25 were found to be possible. Depending on the shape of the aperture (orifice or long opening) and the flow direction, the wind’s impact on the flow changes (exposed inlet or exposed outlet). When the outlet is exposed to external flow, the effect of wind on the Cd value for a lengthy opening is insignificant. Awbi et al. [15] noted that the discharge coefficient value varies depending on the geometry of the opening and the pressure differential owing to external factors. In addition, the variance in Cd indicated that this value varied for several variables; hence, there could be significant inaccuracies in calculating this coefficient. Therefore, it is essential to establish methods for carrying out on-site measurements as accurately and efficiently as possible to reduce such inaccuracies.

According to the natural ventilation principle, air is propelled by the pressure difference across the openings created by thermal buoyancy and wind forces [16]. Bernoulli’s theory states that the pressure difference can be transformed into kinetic energy by assuming a steady incompressible flow, as shown in the equation below:

\[ V_{th} = \sqrt{\frac{2 \cdot \Delta P}{\rho}} \]  \hspace{1cm} (1)

where \( V_{th} \) is the theoretical air velocity through the opening (m/s), \( \Delta P \) is the pressure difference across the opening (Pa), and \( \rho \) is the air density (kg/m\(^3\)). Given the pressure difference, the volume airflow rate (Q) through an opening can be calculated by combining Bernoulli’s equation and the conservation of mass, as follows:

\[ Q = C_d \cdot A \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}} \]  \hspace{1cm} (2)

where \( C_d \) is the dimensionless discharge coefficient of the opening, which is introduced to account for the effects of flow contraction and friction due to viscous forces [17]. The discharge coefficient can be determined by rearranging Eq. (2) to give:

\[ C_d = \frac{Q}{A \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}}} \]  \hspace{1cm} (3)

Therefore, the purpose of this study is to determine the discharge coefficient value for various sash angles, and the impact of the louvre geometric parameter on the discharge coefficient.

### 2 Overview the measurement

#### 2.1 Target building

The measurements were conducted in a naturally ventilated building during summer at various pressure differences, external/internal wind velocities, wind directions, air temperature, and relative humidity. In addition, field measurements were collected in a full-scale experimental building to initiate natural ventilation conditions in an actual building at the environmental laboratory of Kyushu University, Japan, as shown in Figure 1. The examination room was placed on the third floor facing east.

![Fig. 1. Experimental building, Kyushu University.](image)

### 2.2 Measurement setup

The internal dimensions of the chamber were 6500 mm × 4000 mm × 2600 mm, and the measurement configuration in the test room was set up, as shown in Figure 2. The entrance and windows were closed, except for the opening of the louvres. The opening of the louvre was linked to the window frame in the measurement chamber. The measurement periods for the three cases were completed during summer. In addition, cooling or heating were not used during the measurements. Instead, the indoor temperature, relative humidity, and CO\(_2\) concentration were recorded at the center of the room. Louvre openings were opened to assess variations in the interior concentration of the tracer gas. In addition, the average inlet air velocity was determined by measuring the airflow at the center of the louvre ventilation. Because the air velocity fluctuates depending on the position of the inlet, a preliminary experiment was conducted to identify the representative location, and the results demonstrated the typical inlet air velocity of the louvre ventilation. To measure the pressure difference, one of the wind pressure sensors was placed near the opening shape, while another was placed in the center of the room. The outdoor environment was measured, and the devices were positioned on the rooftop of the target building.
The measurement specifications are presented in Table 1. Every measurement section was captured using a data logger at intervals of 5 min.

To determine the effect of the geometrical louver on the ventilation rate and discharge coefficient value, the measurement cases were divided into three categories: louveres with a sash of $0^\circ$, louveres with a sash of $15^\circ$, and louveres with a sash of $30^\circ$, as depicted in Figure 3.

\[ Q_w = \frac{k}{(P_i - P_o)} \]  

where $Q_w$ denotes the ventilation rate, $k$ denotes the generated volume of outgassing, $P_i$ denotes the indoor carbon dioxide concentration, and $P_o$ denotes the outdoor carbon dioxide concentration.

### Table 1. Measurement specification

<table>
<thead>
<tr>
<th>Items</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ concentration</td>
<td>Range of measurement: 0–5000 ppm, accuracy of ±50 ppm, res. = 1 ppm.</td>
</tr>
<tr>
<td>Inlet air velocity</td>
<td>Range of measurement : 0.01–30 m/s, accuracy of 0.02 m/s, res. = 0.01 m/s.</td>
</tr>
<tr>
<td>Pressure difference</td>
<td>Range of measurement : 100–200 hPa, accuracy of 0.001 hPa, res. = 0.1°C.</td>
</tr>
<tr>
<td>Indoor temperature</td>
<td>Range of measurement: 0–5°C, accuracy of ±0.5°C, res. = 0.1°C.</td>
</tr>
<tr>
<td>Indoor RH</td>
<td>Range of measurement: 10–95% RH, accuracy of ±5% RH, res. = 1%.</td>
</tr>
<tr>
<td>Outdoor wind velocity</td>
<td>Range of measurement: 0–75 m/s, accuracy of ±0.3 m/s, res. = 0.1 m/s</td>
</tr>
<tr>
<td>Outdoor wind direction</td>
<td>Range of measurement: 0–359.9°, accuracy of 3°, res. = 0.1°</td>
</tr>
<tr>
<td>Outdoor temperature</td>
<td>Range of measurement: 50–60°C, accuracy of ±0.2°C</td>
</tr>
<tr>
<td>Outdoor RH</td>
<td>Range of measurement: 0–100%, accuracy of ±0.2%.</td>
</tr>
</tbody>
</table>

### 2.3 Natural ventilation rate estimation

Tracer gases are utilized in various diagnostic procedures such as leakage detection, environmental tracing, and building ventilation monitoring [18]. The tracer gas approach can be classified into three types: the constant injection, concentration decay, and constant concentration methods. The concentration approach is extensively used because it requires only the smallest amount of gas and reasonably straightforward equipments. The measurement range of the devices used was 5000 ppm, and the accuracy of the devices was approximately 50 ppm. In this study, we used a CO$_2$ concentration of 3500 ppm [19]. The relationship between the concentration of CO$_2$ produced by natural processes and ventilation rate can be expressed as follows:

### 3 Result and discussion

#### 3.1 Outdoor weather conditions

The average outdoor weather conditions were similar among the tested cases, as shown in Table 2. The outdoor wind velocity ranged from 2.19 m/s to 3.87 m/s, while the average pressure difference was 1.16 Pa for all cases. The mean temperature difference was 3.37°C. As a result, the
temperature difference for all measurement cases was insignificant [5, 20]. This means that the thermal buoyancy effect was not dominant in this study; therefore, the effect of the temperature difference was excluded from the analysis.

### Table 2. Outdoor weather conditions

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor wind velocity</td>
<td>2.87</td>
<td>3.87</td>
<td>2.19</td>
</tr>
<tr>
<td>Temperature difference</td>
<td>3.50</td>
<td>2.76</td>
<td>3.87</td>
</tr>
<tr>
<td>Pressure difference</td>
<td>0.81</td>
<td>1.54</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Meanwhile, the average outdoor wind velocity for the whole summer was 3.54 m/s, with maximum and minimum values of 13.20 m/s and 0 m/s, respectively. Figure 4 shows the changes in outdoor wind velocity during the summer. In addition, the frequencies of the outdoor wind velocity during the summer were analyzed and are shown in Figure 5. Approximately 66% of the measured outdoor wind velocity in the summer was less than 4.0 m/s. This can be explained by the fact that the external wind speed conditions in all cases represented the general summer conditions in the measurement area. As a result, we concluded that the outdoor conditions for the entire summer were similar to those during the measurement periods for each case tested, and the results of this study can be used for the entire summer conditions of naturally ventilated buildings in Fukuoka, Japan.

### 3.2 Comparison of ventilation rate and velocity

Figures 6–8 demonstrate the ventilation rates quantified according to the outdoor wind velocity, inlet air velocity, and theoretical air velocity (Vth). The outdoor wind velocity and inlet air velocity were measured at the rooftop and center of the louver openings, while the theoretical air velocity was calculated based on Eq (1). The mean ventilation rate for all cases was 207.51 m³/h, with maximum and minimum values of 701.85 m³/h and 29.64 m³/h, respectively. Despite the fluctuation of outdoor wind velocity among the cases tested, the results of this study show that the outdoor wind velocity was similar to the ventilation rate, inlet air velocity, and theoretical velocity. The study confirmed that the ventilation rate is affected by the velocities (outdoor wind velocity and inlet air velocity).

**Fig. 4.** Outdoor wind velocity condition.

**Fig. 5.** Frequency of outdoor wind velocity.

**Fig. 6.** Comparison of velocity and ventilation rate case 1.

**Fig. 7.** Comparison of velocity and ventilation rate case 2.

**Fig. 8.** Comparison of velocity and ventilation rate case 3.
3.3 Relationship of ventilation rate, wind velocity, and pressure difference

Figures 9–11 present the relationship between ventilation rate, outdoor wind velocity, and pressure difference. According to outdoor wind velocity, the coefficient of determination \( R^2 \) for all cases tested ranged from 0.35 to 0.84. Then, the correlation coefficient \( R \) was estimated to be between 0.59 and 0.92. This result means that the change in the outlet air velocity was significant concerning the change of ventilation rate in the louvre ventilation opening. A strong relationship between ventilation rate and outdoor wind velocity was observed. Meanwhile, based on pressure difference, the coefficient of determination \( R^2 \) and correlation coefficient \( R \) for all cases averaged to 0.50 and 0.70, respectively.

![Fig. 9. Relationship between ventilation rate and (a) outdoor wind velocity, (b) pressure difference for case 1.](image)

![Fig. 10. Relationship between ventilation rate and (a) outdoor wind velocity, (b) pressure difference for case 2.](image)

![Fig. 11. Relationship between ventilation rate and (a) outdoor wind velocity, (b) pressure difference for case 3.](image)

3.4 Comparison of normalized ventilation rate against the outdoor wind velocity and pressure difference.

As discussed previously, the difference in the ventilation rate of the tested cases shows a significant concern owing to the unstable outdoor wind velocity. Therefore, a normalized ventilation rate \( Q_N \) was utilized to compare the ventilation rate for various external wind velocities and pressure differences among the examined case studies [21, 22]:

\[
Q_N = \frac{Q}{A \cdot U_{ref}}
\]

where \( Q_N \) is the normalized ventilation rate (−), \( Q \) is the ventilation rate (\( \text{m}^3/\text{s} \)), \( U_{ref} \) is the outdoor wind velocity (\( \text{m/s} \)), and \( A \) is the opening dimension of the louvre (\( \text{m}^2 \)). The ventilation rate was transformed into \( Q \) (\( \text{m}^3/\text{s} \)) before
normalization using Eq. (5). Figure 12 shows a comparison of the normalized ventilation rate with outdoor wind velocity. The separation point of the normalized ventilation rate among the cases was clearly observed when the outdoor velocity was above 4 m/s. This means that a constant ventilation rate occurred at outdoor wind velocities above 2 m/s. Even though the ventilation rate fluctuated when the outdoor wind velocity was low, the result mentions that Case 1 had the highest ventilation rate, followed by Cases 2 and 3. Interestingly, the results of this study confirmed that adding a sash with various angles to the louvre mainly affected the ventilation rate.

A comparison of the normalized ventilation rate with the pressure difference is shown in Figure 13. The normalized ventilation rate continued to change until the pressure difference was less than 1 Pa. Case 2 exhibited the highest ventilation rate at this stage. However, when the pressure difference was above 1 Pa, Case 1 was the highest, followed by Cases 2 and 3. This means that a stable value of the normalized ventilation rate occurred when the pressure difference was greater than 1 Pa. As a result, according to the pressure difference, installing a sash in the louvre opening also affected the normalized ventilation rate of the louvre openings.

3.5 The discharge coefficient

Figures 14–16 present the unsteady behavior of the discharge coefficient for the three cases and correspond to the inlet air velocity. The behavior of the discharge coefficient was calculated using Eq (3). Wind turbulence caused the unsteady behavior in the inlet air velocity and pressure difference. Nevertheless, it has been proven that the turbulence patterns for the inlet air velocity and pressure difference are not identical because of the influence of wind on these quantities. Consequently, the calculated discharge coefficient also exhibited unsteady behavior instead of a constant one. The maximum and minimum values of discharge coefficients for Case 1 were reported at 0.51 and 1.14, respectively. Interestingly, the discharge coefficient value tends to decrease with the addition of the sash angle of the louvre openings. As a result, Case 2, installed with a sash angle of 15° in the louvre, showed less discharge coefficient value than that of Case 1, with minimum and maximum at 0.27 and 1.23, respectively. In addition, the maximum and minimum discharge coefficient values for Case 3 with a sash angle of 30° were 0.26 and 0.57, respectively. Moreover, this result is similar to that of a previous study by Iqbal et al. [13] in which the discharge coefficient decreased with increasing sash opening angle in a fully formed turbulent flow of the central pivot roof window. Therefore, the standard discharge coefficient value for the louvre opening in this study was averaged to overcome the result.
Furthermore, the discharge coefficient was evaluated based on outdoor wind velocity and pressure difference. Figure 17 and 18 present the ratio of the discharge coefficient among the cases tested based on the outdoor wind velocity and pressure difference. The discharge coefficient value continued to change according to the outdoor wind velocity, as shown in Figure 17. However, this study reveals that the discharge coefficient value is constant when the outdoor velocity reaches a stable and fixed position of the flow separation points at 2.5 m/s. As a result, Case 1 had the highest Cd value, followed by Cases 2 and 3. Meanwhile, according to the pressure difference, as shown in Figure 18, the discharge coefficient still fluctuated while the pressure difference value was below 1 Pa, where case 2 had the highest discharge coefficient, followed by cases 1 and 3. However, the discharge coefficient value is stable when the pressure difference is almost 1 Pa, with case 1 having the highest value, followed by cases 2 and 3. This result maintained a constant discharge coefficient until the pressure difference exceeded 3 Pa. In addition, the discharge coefficient decreased when the pressure difference was high. These findings are typical for natural ventilation measurements, owing to ordinary natural ventilation conditions.

By contrast, Heiselberg et al. [11] reported Cd reduction when the pressure difference increased, and an almost stable value was obtained when the pressure was above 10 Pa. It is evident that the pressure difference values were mainly below the threshold value of 10 Pa. The authors emphasize that pressure fluctuations of less than 10 Pa are common in the actual measurement of natural ventilation. Therefore, the discharge coefficient value observed in these experiments was considerable for naturally ventilated building settings. Furthermore, this study is significant for actual ventilation conditions, particularly louvre openings with a sash installed. As a result, we can conclude that the discharge coefficient value was average according to the outdoor wind velocity and the pressure difference, where case 1 had the highest discharge coefficient value at 0.80, followed by Cases 2 and 3 at 0.62 and 0.41, respectively.

4 Conclusions

The objective of this study is to evaluate the discharge coefficients for louvre openings with various sash angle installations according to the pressure difference and outdoor wind velocity in real-time measurements. The constant concentration method for CO₂ quantifies the ventilation rate in an indoor environment. Three cases of louvre openings are presented: (1) louvre opening with a sash angle of 0°, (2) louvre opening with a sash angle of 15°, and (3) louvre opening with a sash angle of 30°. The conclusions of this study are as follows:

1. The ventilation rate has a tendency similar to that of the inlet air velocity, outdoor wind velocity, and theoretical velocity.
2. The normalized ventilation rate fluctuated according to the outdoor wind velocity and the pressure difference. A constant value for the airflow rate occurred when the outdoor velocity was above 2 m/s and the pressure difference was greater than 1 Pa.
3. The discharge coefficient of the louvre opening with the installation of the sash varied according to the angle. The value decreased with increasing sash angle, and the summary values of the discharge coefficient for louvres with sash angles of 0°, 15°, and 30° were 0.80, 0.62, and 0.41, respectively.
The findings presented in this study are aimed at understanding the geometrical patterns of louvre ventilation openings and their effects on the ventilation rate and discharge coefficient value according to outdoor wind velocity and pressure difference. These findings can be implemented for houses in tropical climates to increase the indoor thermal environment of naturally ventilated buildings, especially in Indonesia. In future studies, verification of the accuracy of ventilation rate, temperature, relative humidity, and absolute humidity using numerical simulation with a network airflow model will be developed to improve the design of louvre openings in naturally ventilated buildings.

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