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Mass Flow Rate through a Horizontal Opening at Small Pressure Differences

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Highlights:

- A series of model scale experiments were carried out in order to investigate the flow behavior of air and smoke through and around a horizontal opening. If the pressure difference is small, the flow could be bi-directional and/or fluctuating.
- The critical pressure differences for uni-directional flow were measured and correlated with the buoyancy of the smoke layer.
- Engineering relationships to calculate mass flow rate under bi-directional flow were developed by comparison with experimental results.

Abstract:

The smoke and air flow through a horizontal opening was investigated using a model-scale room equipped with a horizontal opening on the ceiling. A smoke layer was created under the ceiling using a small gas burner. The pressure difference across the horizontal opening was changed by controlling the air supply to and exhaust from the space above the opening. Smoke and air flow patterns were either downward uni-directional flow of air, bi-directional flow of air and smoke or uni-directional flow of smoke upward. By changing the pressure difference across the opening, critical pressure differences to cause uni-directional flow were determined. It was found that the critical pressure was 0.98 of the smoke layer buoyancy for the onset of upward uni-directional smoke flow, and 0.47 for downward uni-directional air flow. From the measured carbon dioxide concentration, the mass flow rates of smoke and air were calculated and correlated with the non-dimensional pressure difference in the case of bi-directional flows.

Keywords: horizontal opening, bi-directional flow, fluctuating flow, critical pressure differences, mass flow rate

Nomenclature

\begin{tabular}{ll}
\textit{D} & size of opening [m] \\
\textit{Fr} & Froude number (non-dimensional mass flow rate) [-] \\
\textit{g} & gravitational constant [m/s\(^2\)] \\
\textit{H_{smoke}} & thickness of the smoke layer [m] \\
\textit{m} & mass flow rate [kg/s] \\
\textit{m_{air}} & mass flow rate of air flowing downward through an opening [kg/s] \\
\textit{m_{smoke}} & mass flow rate of smoke flowing upward through an opening [kg/s] \\
\end{tabular}

\textbf{Greek letters}

\begin{tabular}{ll}
\textit{\alpha} & orifice coefficient (=0.7) \\
\textit{\Delta P} & pressure difference across an opening [Pa] \\
\textit{\Delta P_{flood}} & critical pressure difference for flooding [Pa] \\
\textit{\Delta T} & average temperature rise in smoke layer [\^\circ C] \\
\textit{\rho} & density of fluid flowing through an opening [kg/m\(^3\)] \\
\textit{\rho_{ave}} & average density of outside air and \\
\end{tabular}
1. Introduction

The use of a ceiling smoke vent is one of the practical ways for smoke control in building atriums. If the smoke layer is thick enough and the smoke layer temperature is high enough, the ceiling vent is very efficient for exhausting smoke. Flow will be uni-directional as shown in Fig. 1a). However, if the thickness and temperature of the smoke layer are not high enough, flow through the ceiling vent will be unstable. Bi-directional flow or fluctuating flow may take place as shown in Fig.1b) and 1c).

Epstein [1] carried out a series of experiments using a salt-water bath with one or two horizontal openings of different depth and width. Cooper [2,3] developed a semi-theoretical model to calculate the exchange flow rate based on the experimental work including that of Epstein. In the formulation, the rate of exchange of flow was added if the pressure difference was small. The critical pressure difference to cause uni-directional flow was determined as the flooding pressure difference. Further experimental research has been conducted by many authors. Tu et al. [4] carried out experiments with a single horizontal opening and compared their results with Cooper's calculation method. Tan and Jaluria [5,6] measured exchange flow rates using a water bath. Chen et al.[7] observed the behavior of oscillating flow through a horizontal opening by using a laser sheet. In their experiments, the fire plume was placed right below the opening. Frequency of oscillation of vent flow and pulsation of flame were correlated with opening size. Prétrel et al. conducted an extensive set of experiments with detailed observations and measurements of flow patterns through a horizontal vent. The results were compared with Cooper's correlation and the need for improvements were specified [8,9,10]. Yamada [11] conducted model scale experiments of fire in a room with a single opening on the ceiling. Air was supplied to the fire room and the critical pressure difference to create uni-directional upward

\[
\begin{align*}
T_{air} & \quad \text{outside air temperature [K]} \\
T_{smoke} & \quad \text{smoke layer temperature [K]} \\
V & \quad \text{volumetric flow rate [m}^3/\text{s}] \\
V_{air} & \quad \text{volumetric flow rate of air from the upper room to the lower room [m}^3/\text{s}] \\
V_{ex} & \quad \text{volumetric flow rate of exhaust gas from the upper room [m}^3/\text{s}] \\
V_{smoke} & \quad \text{volumetric flow rate of smoke from the fire room to the upper room [m}^3/\text{s}] \\
V_{supply} & \quad \text{volumetric flow rate of supply air to the upper room [m}^3/\text{s}] \\
\rho_{air} & \quad \text{density of outside air [kg/m}^3]\right] \\
\rho_{smoke} & \quad \text{density of smoke in the smoke layer in the fire room [kg/m}^3]\right] \\
\Delta \rho & \quad \text{density difference between the upper room air and smoke in the upper layer in the fire room [kg/m}^3]\right] \\
\Pi & \quad \text{non-dimensional pressure [-]} \\
\Pi_{flood} & \quad \text{critical non-dimensional pressure for uni-directional flow [-]} \\
\text{Subscripts} & \quad \text{supply supply air} \\
& \quad \text{flood flooding} \\
& \quad \text{ex exhaust} \\
& \quad \text{smoke smoke} \\
& \quad \text{air air} \\
& \quad \text{net net flow rate}
\end{align*}
\]
flow was measured. In his experiments, the fire plume was put right below the bottom of the ceiling opening. Thus the effect of the momentum of the plume was included.

The most crucial case involves a horizontal opening far from a fire plume. The upward flow is driven only by the buoyancy of the smoke layer of a certain thickness. In practical design, the effectiveness of a horizontal opening should be estimated against smoke layer thickness and temperature. A general relationship between pressure difference and flow rate is not well known yet especially when the smoke layer thickness is small. In this study, a series of experiments was carried out to investigate the flow patterns through a horizontal opening. The critical pressure differences to cause uni-directional flow were measured and correlated with the buoyancy of the smoke layer. Furthermore, the mass flow rates in the case of bi-directional flows were measured and correlated with pressure differences.

2. Experimental Methods

A series of model scale experiments was carried out to determine the onset of unstable bi-directional flows and to measure the mass flow rates under bi-directional conditions.

2.1 Experimental apparatus

Schematics of the experimental apparatus are shown in Fig. 2. The apparatus consists of two rooms, the fire room and the upper room. A horizontal opening, 100mm square, is provided in the ceiling of the fire room. The thickness of the opening is 12.5mm. It is known that the ratio of thickness to diameter affect the flow pattern [1], this work focuses only on shallow openings. A photographic view of the fire room is shown in Fig.3. The room contains a gas burner to simulate a fire source. Smoke from the gas burner creates a smoke layer. One side of the fire room was a large opening with a 50mm-deep smoke curtain. Most of the smoke flowed out but a certain amount of smoke accumulated under the ceiling. The ceiling and the upper part of the walls were insulated by ceramic fiber board of 25mm thickness in order to avoid cooling of the smoke.

The upper room is a closed space. Smoke from the horizontal opening accumulates under a smoke-collecting hood and is exhausted to outside of the room. Fresh air is supplied to the lower portion of the upper room. By changing the volume flow rates of exhaust smoke and supply air, the upper room pressure is controlled.

To obtain the mass flow rate of smoke flowing upward through the horizontal opening, carbon dioxide concentrations were measured in the smoke layer, the exhaust air and the supply air. At the same time, volume flow rates of exhaust smoke and supply air were measured by orifice flow meters. To determine the interface position of the smoke layer, vertical temperature and carbon dioxide concentration profiles were measured. The pressure difference across the horizontal opening was measured by a micro manometer (9.8 Pa range) placed at the same height as the
ceiling board. As the pressure differences were small, the manometer was adjusted carefully. The pressure sampling tubes were installed horizontally in order to avoid errors due to buoyancy in the sampling tubes.

To investigate the flow behavior around the opening, the temperature profile is measured using a two-dimensional mesh. The mesh size was 50mm. Thin thermocouples, 0.32mm in diameter, were used to reduce the effect of radiation upon the thermocouples.

![Fig. 2 Schematics of experimental apparatus]

![Fig. 3 View of the fire room]

2.2 Determination of critical pressure differences for uni-directional flow
The flow behaviors at the horizontal opening were observed by using white particles as shown in Fig. 4. For each experimental run, the flow pattern was classified either as uni-directional flow or bi-directional flow. The critical pressure differences for uni-directional flow were designated as the critical pressure difference for flooding, $\Delta P_{\text{flood}}$. Positive values correspond with smoke flow upward, while negative values correspond with air flow downward.

Fig. 4 Visualization of smoke by white particles

### 2.3 Determination of mass flow rates of air and smoke

Approximating that the density difference between air and smoke is small, conservation of volume can be used instead of mass conservation. The conservation of total gas gives

$$V_{\text{smoke}} + V_{\text{supply}} = V_{\text{air}} + V_{\text{ex}}.$$  \hspace{1cm} (1)

The conservation of carbon dioxide gives

$$Y_{\text{smoke}} V_{\text{smoke}} + Y_{\text{supply}} V_{\text{supply}} = Y_{\text{ex}} V_{\text{air}} + Y_{\text{ex}} V_{\text{ex}}.$$ \hspace{1cm} (2)

Solving for volumetric flow rates of air $V_{\text{air}}$ and smoke $V_{\text{smoke}}$, we determine that

$$V_{\text{smoke}} = \frac{Y_{\text{ex}} - Y_{\text{supply}}}{Y_{\text{smoke}} - Y_{\text{ex}}} V_{\text{supply}}.$$ \hspace{1cm} (3)

$$V_{\text{air}} = \frac{Y_{\text{smoke}} - Y_{\text{supply}}}{Y_{\text{smoke}} - Y_{\text{ex}}} V_{\text{supply}} - V_{\text{ex}}.$$ \hspace{1cm} (4)

Multiplying by the densities of air or smoke,

$$m_{\text{smoke}} = \rho_{\text{smoke}} V_{\text{smoke}} = \frac{353}{T_{\text{smoke}}} \frac{Y_{\text{ex}} - Y_{\text{supply}}}{Y_{\text{smoke}} - Y_{\text{ex}}} V_{\text{supply}}.$$ \hspace{1cm} (5)

$$m_{\text{air}} = \rho_{\text{air}} V_{\text{air}} = \frac{353}{T_{\text{air}}} \left( \frac{Y_{\text{smoke}} - Y_{\text{supply}}}{Y_{\text{smoke}} - Y_{\text{ex}}} V_{\text{supply}} - V_{\text{ex}} \right).$$ \hspace{1cm} (6)

### 3 Experimental conditions and results
Experiments were carried out under steady state conditions of the smoke layer thickness and temperature. The smoke layer temperature was selected as an experimental parameter. Setting smoke layer temperature to a prescribed value, the pressure difference was varied. The resulting flow patterns were observed and flow rates were measured.

### 3.1 Results at temperature difference 15K (Series A)

#### 3.1.1 Experimental conditions

As shown in Table 1, the smoke layer temperature was kept about 15K higher than the ambient temperature. Smoke layer thickness was about 130mm. Nineteen experiments were carried out by changing the pressure difference. The experiments are numbered in the order of execution, but sorted in the order of the pressure difference in Table 1.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>supply air $V_{\text{supply}}$ [m³/s]</th>
<th>CO₂ conc. $Y_{\text{supply}}$ [%]</th>
<th>exhaust smoke $V_{\text{ex}}$ [m³/s]</th>
<th>CO₂ conc. $Y_{\text{ex}}$ [%]</th>
<th>smoke layer thickness $H_{\text{smoke}}$ [m]</th>
<th>temp. rise above ambient $\Delta T$ [K]</th>
<th>CO₂ conc. smoke layer $Y_{\text{smoke}}$ [%]</th>
<th>opening pressure difference $\Delta P$ [Pa]</th>
<th>CO₂ conc. outside air $Y_{\text{air}}$ [%]</th>
<th>temp. outside air $T_{\text{air}}$ [°C]</th>
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<td>0.0145</td>
<td>0.065</td>
<td>0.0120</td>
<td>0.066</td>
<td>0.125</td>
<td>15.2</td>
<td>0.110</td>
<td>-0.094</td>
<td>0.072</td>
<td>14.0</td>
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<td>0.077</td>
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<td>0.098</td>
<td>-0.083</td>
<td>0.081</td>
<td>14.8</td>
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<td>0.078</td>
<td>0.0100</td>
<td>0.079</td>
<td>0.136</td>
<td>14.3</td>
<td>0.103</td>
<td>-0.063</td>
<td>0.083</td>
<td>14.9</td>
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<td>0.059</td>
<td>0.0136</td>
<td>0.058</td>
<td>0.128</td>
<td>13.7</td>
<td>0.095</td>
<td>-0.046</td>
<td>0.061</td>
<td>14.0</td>
</tr>
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<td>A-9</td>
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<td>0.073</td>
<td>0.0124</td>
<td>0.072</td>
<td>0.132</td>
<td>13.9</td>
<td>0.090</td>
<td>-0.025</td>
<td>0.074</td>
<td>14.6</td>
</tr>
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<td>0.057</td>
<td>0.0142</td>
<td>0.060</td>
<td>0.129</td>
<td>11.6</td>
<td>0.085</td>
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<td>0.072</td>
<td>0.0132</td>
<td>0.073</td>
<td>0.131</td>
<td>13.9</td>
<td>0.085</td>
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<td>0.099</td>
<td>0.001</td>
<td>0.081</td>
<td>14.8</td>
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<td>13.9</td>
<td>0.097</td>
<td>0.003</td>
<td>0.063</td>
<td>15.0</td>
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<td>A-15</td>
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<td>0.065</td>
<td>0.0149</td>
<td>0.073</td>
<td>0.126</td>
<td>14.5</td>
<td>0.105</td>
<td>0.023</td>
<td>0.068</td>
<td>14.0</td>
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<td>0.080</td>
<td>0.0149</td>
<td>0.091</td>
<td>0.130</td>
<td>13.4</td>
<td>0.099</td>
<td>0.029</td>
<td>0.083</td>
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<td>0.0148</td>
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<td>0.133</td>
<td>13.4</td>
<td>0.094</td>
<td>0.040</td>
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<td>0.057</td>
<td>0.078</td>
<td>14.6</td>
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<td>0.0151</td>
<td>0.080</td>
<td>0.126</td>
<td>11.0</td>
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<td>0.081</td>
<td>0.067</td>
<td>13.5</td>
</tr>
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<td>0.066</td>
<td>0.0152</td>
<td>0.082</td>
<td>0.124</td>
<td>10.4</td>
<td>0.078</td>
<td>0.101</td>
<td>0.066</td>
<td>13.5</td>
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<td>A-7</td>
<td>0.0113</td>
<td>0.095</td>
<td>0.0145</td>
<td>0.115</td>
<td>0.125</td>
<td>13.3</td>
<td>0.095</td>
<td>0.111</td>
<td>0.093</td>
<td>16.3</td>
</tr>
</tbody>
</table>

* positive when the fire room pressure is higher than the upper room pressure.

#### 3.1.2 An example of measured results

Results of Exp. A-12 are examined in this section. Part of the measured data is shown in Fig.5. After setting the measuring devices, the data logger was started. At 3 minutes, air supply and smoke exhaust fans were started. As shown in Fig.5a), the air supply rate was larger than the smoke exhaust rate. Thus the upper room was slightly pressurized. As a result, the pressure difference was measured as negative values around -0.1Pa. At 1,900 seconds, the gas burner was ignited. As shown in Fig.5b), temperature in the lower room began to rise. After around 5,400 seconds, the smoke layer temperature seemed to be stabilized and stratified. Temperature at the
ceiling surface and 40mm below ceiling were the highest. At lower positions, temperatures were lower and close to that in the outside air.

After making sure that the temperature reached steady state, temperatures from 6,300 and 6,420 seconds were simply averaged. Carbon dioxide concentrations were measured thereafter.

Measured temperature and carbon dioxide concentration profiles are shown in Fig.6. The hot smoke layer was formed in the upper part of the fire room. A fairly sharp interface formed at

---

**Fig.5** Measured raw data of Exp. A-12

**Fig.6** Measured raw data of Exp. A-12
around 0.11 to 0.12 meters below the ceiling. Using the N%-method (N=15) [12], the smoke layer thickness and smoke layer temperature were determined as

\[ H_{\text{smoke}} = 0.125 \, \text{m}, \]  
\[ T_{\text{smoke}} = 29.2 \, ^\circ\text{C}. \]

Using the N%-method (N=15) [12], the smoke layer thickness and smoke layer temperature were determined as

There was also a sharp interface in the profile of carbon dioxide concentration. Considering that the major mixing with air takes place in the upper part of the smoke layer, the bottom of smoke layer was assumed to be located where the concentration rise corresponds with 1/3 of the maximum concentration rise. Averaging the carbon dioxide concentration over the smoke layer thickness, the average carbon dioxide concentration was

\[ Y_{\text{smoke}} = 0.182 \% \]

Using equations (5) and (6), the mass flow rates of smoke and air were

\[ m_{\text{smoke}} = \frac{353 \times (0.066 - 0.065)}{29.2 + 273.2} \times 0.145 = 0.00015 \, \text{kg/s}, \]  
\[ m_{\text{air}} = \frac{353 \times (0.182 - 0.065)}{13.9 + 273.2} \times 0.145 - 0.0122) = 0.0308 \, \text{kg/s}. \]

![Graph showing vertical profiles of temperature and CO₂ concentration at steady state (6,300-6,420 seconds)](https://example.com/graph.png)

**3.1.3 Typical flow patterns and critical pressure differences for flooding**

The observed flow direction and temperature contours are shown in Fig.7. When the pressure difference is –0.094 Pa, flow was unidirectional as shown in A-12. When the pressure difference was in the range of -0.083 to 0.040Pa as shown in A-18, A-1 and A-6, bi-directional flow or fluctuating flow were observed. When the pressure difference was more than 0.057, flow was
upward unidirectional as shown in A-16. The boundaries between uni-directional and bi-
directional flows, the critical pressure differences for flooding were found to be 0.049Pa for
upward flow, -0.088Pa for downward flow.

![Typical flow patterns and temperature contours in Series A](image)

**Fig. 7** Typical flow patterns and temperature contours in Series A

### 3.1.4 Mass flow rates

Using the measured CO$_2$ concentrations shown in Table 1, smoke and air flow rates were
calculated by equations (6) and (5). The measured volume flow rates are shown in Table 2 and
Fig. 8. The critical pressure differences for flooding were 0.049Pa for upward smoke flow, -
0.088Pa for downward air flow. The value on positive side coincided with that calculated by
Cooper's formula[3],

$$
\Delta p_{\text{flood}} = 0.9708 \Delta \rho g D (1 + \frac{1}{2} \frac{\Delta \rho}{\rho_{\text{ave}}} ) \exp(1.1072 \frac{\Delta \rho}{\rho_{\text{ave}}}) = 0.044 \text{ Pa},
$$

(12)

where the average density of smoke and air was calculated by

$$
\rho_{\text{ave}} = 353 \div [(T_{\text{smoke}} + T_{\text{air}}) / 2] = 353 / 301 = 1.20 \text{ kg/m}^3.
$$

(13)

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>pressure difference $\Delta P$ [Pa]</th>
<th>flow rate</th>
<th>flow pattern*</th>
<th>critical pressure difference for</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>smoke (upward)</td>
<td>air (downward)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Measured mass flow rates in Series A
Fig. 8 Measured volumetric flow rates in Series A

The solid line in Fig. 8 denotes the flow rates calculated by simple orifice theory

\[ m = \alpha A \sqrt{2 \rho_{\text{ave}} \Delta P} = 0.7 \times 0.01 \sqrt{2 \times 1.20 \times \Delta P} = 0.0108 \sqrt{\Delta P}. \]
The measured mass flow rates agreed well with the orifice theory if the pressure difference is larger than the critical pressure difference for flooding.

When the pressure difference is smaller than the critical pressure difference for flooding, upward and downward flow rates were obtained by equations (5) and (6). Upward flow exists at pressure differences larger than -0.017 Pa. Due to buoyancy, part of the smoke could flow upward even though the pressure difference is slightly negative. Similarly the downward air flow cannot enter the fire room unless the pressure difference is slightly negative. At pressure differences between -0.02 and 0 Pa, upward smoke flow and downward air flow co-exist.

3.2 Critical pressure differences for various smoke layer temperatures (Series B to I)

The same procedures were repeated varying the smoke layer temperature to 20, 25 and 28 K above ambient. The results are summarized in Table 3 and Table 4. In these series, critical pressure differences were determined by visual observation. Due to the excessive work, flow rates were not wholly measured. However the critical pressure differences for flooding could be extracted and correlated with the buoyancy of the smoke layer, \( \Delta p g H_{\text{smoke}} \) [Pa].

The results are shown in Fig. 9. Positive values correspond with critical pressure differences for upward unidirectional flow. The critical pressure differences seem to be proportional to the buoyancy of the smoke layer, \( \Delta p g H_{\text{smoke}} \). Linear regression gives the factor 0.98. The negative values correspond with downward unidirectional flow. Regression gives the factor 0.47. In non-dimensional form, the relationships are

\[
\Pi_{\text{flood}} = \frac{\Delta P_{\text{flood}}}{\Delta \rho g H_{\text{smoke}}} = \begin{cases} 
0.98 & \text{(upward flooding)} \\
-0.47 & \text{(downward flooding)} 
\end{cases} 
\]

Table 3 Experimental Results for temperature differences 20, 25 and 30 K (Series B, C, D and E)[13]
Table 4 Experimental Results for temperature differences 10, 15 and 20K (Series F, G, H and I) [14]

<table>
<thead>
<tr>
<th>series</th>
<th>Exp. No.</th>
<th>Smoke layer</th>
<th>pressure difference ΔP [Pa]</th>
<th>Flow rate</th>
<th>flow pattern*</th>
<th>critical pressure difference for flooding ΔP_flood [Pa]</th>
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<tbody>
<tr>
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* DU: Downward Uni-directional flow, DF: Downward Fluctuating flow, B: Bi-directional flow, UF: Upward Fluctuating flow, UU: Upward Uni-directional flow

Fig. 9 Critical pressure differences for uni-directional flow

3.3 Mass flow rates in the case of bi-directional flows

To develop an engineering relationship, measured mass flow rates were correlated with pressure difference in non-dimensional form using non-dimensional pressure and non-dimensional velocity (Froude number) determined by

\[ \Pi = \frac{\Delta P}{\Delta \rho g H_{smoke}}, \]  

(16)

\[ Fr = \left( \frac{m}{\rho D^2} \right) / \sqrt{2 \Delta \rho g H_{smoke} / \rho_{ave}}. \]  

(17)

Consistent with equations (16) and (17), all the measured mass flow data in Table 3 and Table 4 are plotted in Fig. 10. In spite of the differences in smoke layer temperature, all the data tend to gather on a single line. Using the definitions of equations (16) and (17), the simple orifice flow equation (14) can be transformed to non-dimensional form as

\[ Fr = 0.7 \sqrt{\Pi}. \]  

(18)
Fig. 10 non-dimensional mass flow rate as functions of non-dimensional pressure difference

Equation (18) is also plotted in Fig. 10 by a solid line. If the pressure difference is larger than critical pressure difference for flooding, flow rate is similar to that calculated by simple orifice theory. If the pressure difference is small and bi-directional flow is observed, the measured values of mass flow rates deviate from that of simple orifice theory. It seems that the onset of bi-directional flow deviated to negative side of the pressure as shown by the dashed lines. To represent the center of the data, the formula between critical pressures on the positive and negative sides were modified as

\[
F_{\text{smoke}} = \begin{cases} 
0 & (\Pi \leq -0.3) \\
\frac{1}{1.28} \left(\frac{\Pi + 0.3}{0.98}\right) & (-0.3 < \Pi \leq 0.98), \\
\sqrt{\Pi} & (0.98 < \Pi) 
\end{cases} 
\] (19)

\[
F_{\text{air}} = \begin{cases} 
\sqrt{-\Pi} & (\Pi \leq -0.47) \\
\frac{1}{0.37} \left(\frac{\Pi + 0.1}{-0.47}\right) & (-0.47 < \Pi \leq -0.1), \\
0 & (-0.1 < \Pi) 
\end{cases} 
\] (20)

which are shown by the dashed lines in Fig.10.

4. Conclusions

Model-scale experiments were carried out to investigate the flow behavior through a horizontal opening above a smoke layer. The findings are summarized as follows:

- The flow was either uni-directional, bi-directional or fluctuating. When the pressure difference was small, flow was bi-directional or fluctuating. The critical pressure differences for flooding for uni-directional flow were determined by visual observation.
- The critical pressure differences for flooding were correlated with the buoyancy of the smoke layer. The ratios were 0.98 for upward uni-directional flow, and 0.47 for downward uni-directional flow.

- The mass flow rates of smoke and air under bi-directional flow were normalized by a non-dimensional pressure and a non-dimensional velocity (Froude number). An engineering equation set was developed by moving the origin of the orifice flow equation towards the negative side of the pressure difference consistent with the observed data.

5. Acknowledgements

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6. References


