

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

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

Greek letters

α	orifice coefficient (=0.7)
ΔP	pressure difference across an opening [Pa]
ΔP_{flood}	critical pressure difference for flooding [Pa]
ΔT	average temperature rise in smoke layer [$^{\circ}\text{C}$]
ρ	density of fluid flowing through an opening [kg/m^3]
ρ_{ave}	average density of outside air and

T_{air}	outside air temperature [K]		smoke in the upper layer [kg/m^3]
T_{smoke}	smoke layer temperature [K]	ρ_{air}	density of outside air [kg/m^3]
V	volumetric flow rate [m^3/s]	ρ_{smoke}	density of smoke in the smoke layer in the fire room [kg/m^3]
V_{air}	volumetric flow rate of air from the upper room to the lower room [m^3/s]	$\Delta\rho$	density difference between the upper room air and smoke in the upper layer in the fire room [kg/m^3]
V_{ex}	volumetric flow rate of exhaust gas from the upper room [m^3/s]	Π	non-dimensional pressure [-]
V_{smoke}	volumetric flow rate of smoke from the fire room to the upper room [m^3/s]	Π_{flood}	critical non-dimensional pressure for uni-directional flow [-]
V_{supply}	volumetric flow rate of supply air to the upper room [m^3/s]	Subscripts	
Y	concentration of carbon dioxide [-]	$supply$	supply air
Y_{ex}	concentration of carbon dioxide in the exhaust gas [-]	$flood$	flooding
Y_{smoke}	concentration of carbon dioxide in the smoke layer [-]	ex	exhaust
Y_{supply}	concentration of carbon dioxide in the supply air [-]	$smoke$	smoke
		air	air
		net	net flow rate

30

31 1. Introduction

32 The use of a ceiling smoke vent is one of the practical ways for smoke control in building
33 atriums. If the smoke layer is thick enough and the smoke layer temperature is high enough, the
34 ceiling vent is very efficient for exhausting smoke. Flow will be uni-directional as shown in Fig.
35 1a). However, if the thickness and temperature of the smoke layer are not high enough, flow
36 through the ceiling vent will be unstable. Bi-directional flow or fluctuating flow may take place
37 as shown in Fig.1b) and 1c).

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

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.

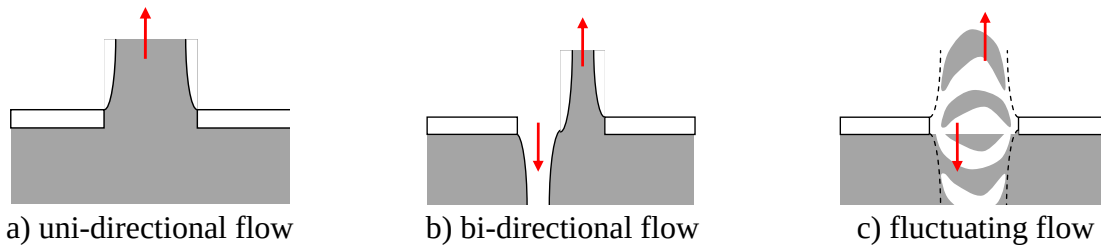


Fig. 1 Typical flow patterns

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.

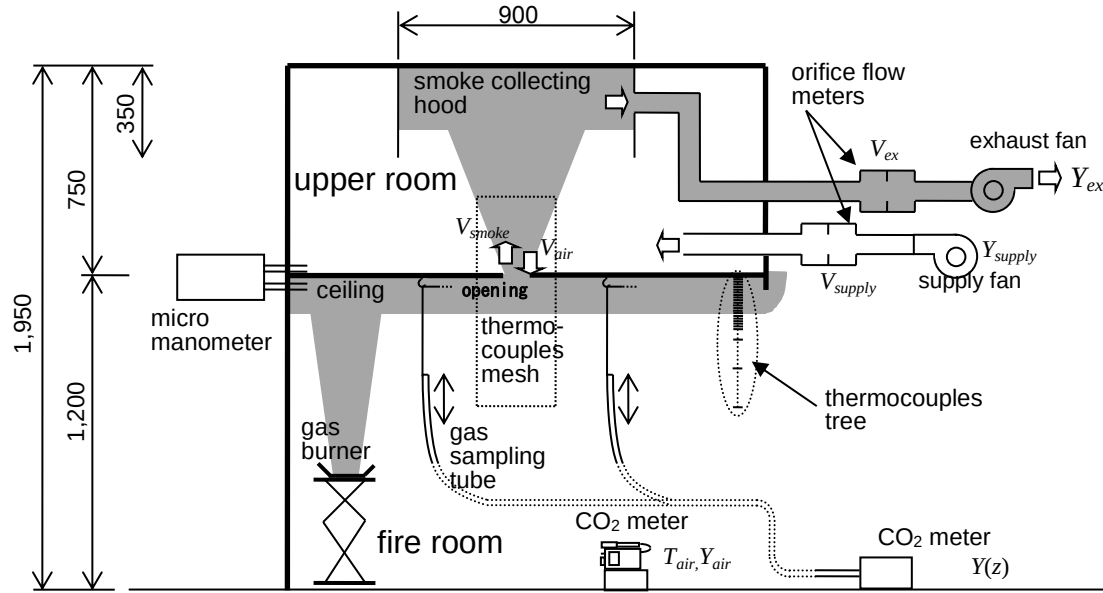


Fig. 2 Schematics of experimental apparatus

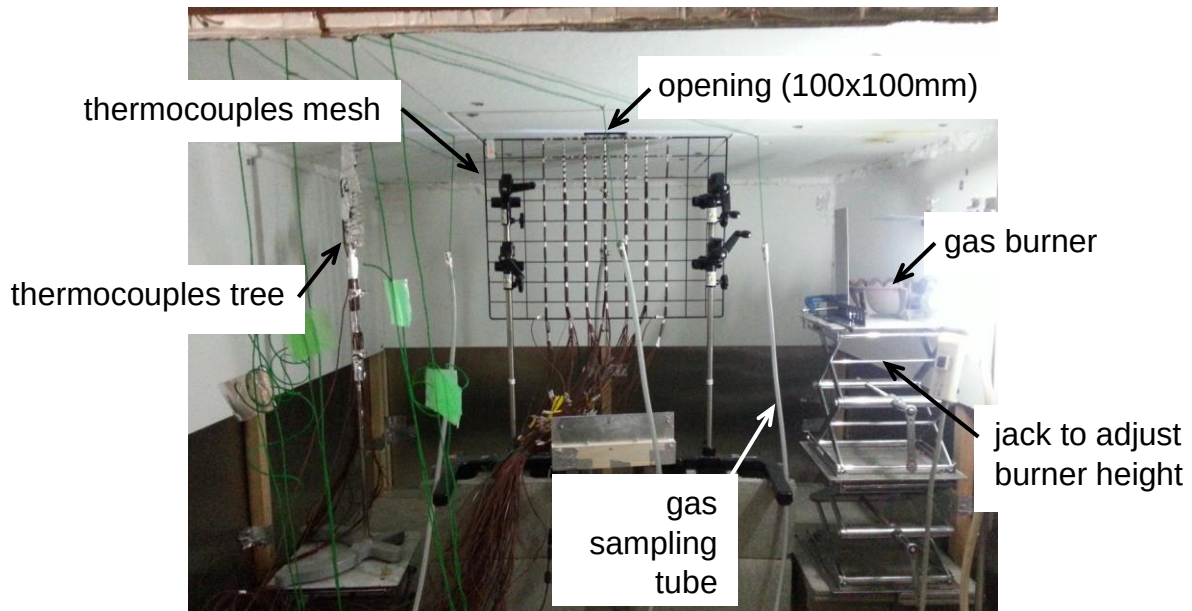


Fig. 3 View of the fire room

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, ΔP_{flood} . Positive values correspond with smoke flow upward, while negative values correspond with air flow downward.

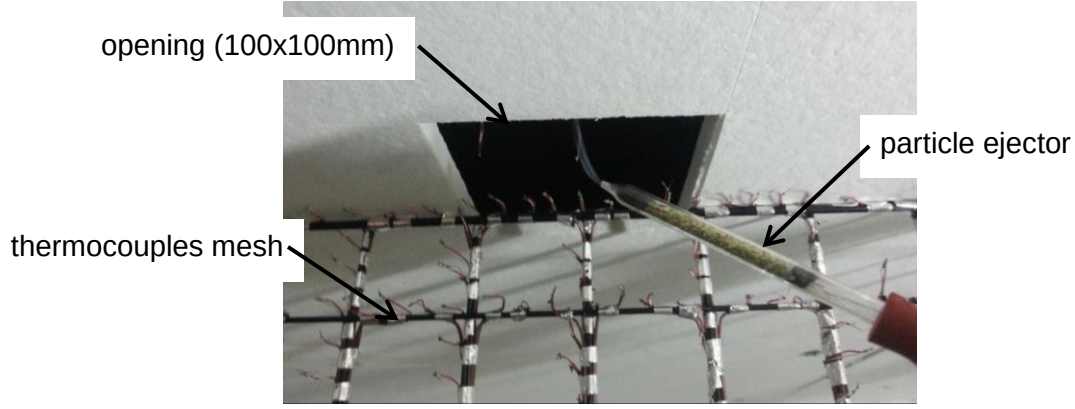


Fig. 4 Visualization of smoke by white particles

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

$$V_{smoke} + V_{supply} = V_{air} + V_{ex} . \quad (1)$$

The conservation of carbon dioxide gives

$$Y_{smoke} V_{smoke} + Y_{supply} V_{supply} = Y_{ex} V_{air} + Y_{ex} V_{ex} . \quad (2)$$

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

$$V_{smoke} = \frac{Y_{ex} - Y_{supply}}{Y_{smoke} - Y_{ex}} V_{supply} . \quad (3)$$

$$V_{air} = \frac{Y_{smoke} - Y_{supply}}{Y_{smoke} - Y_{ex}} V_{supply} - V_{ex} , \quad (4)$$

Multiplying by the densities of air or smoke,

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

$$m_{air} = \rho_{air} V_{air} = \frac{353}{T_{air}} \left(\frac{Y_{smoke} - Y_{supply}}{Y_{smoke} - Y_{ex}} V_{supply} - V_{ex} \right) , \quad (6)$$

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 1 Experimental conditions in Series A ($\Delta T=15K$, approx.)

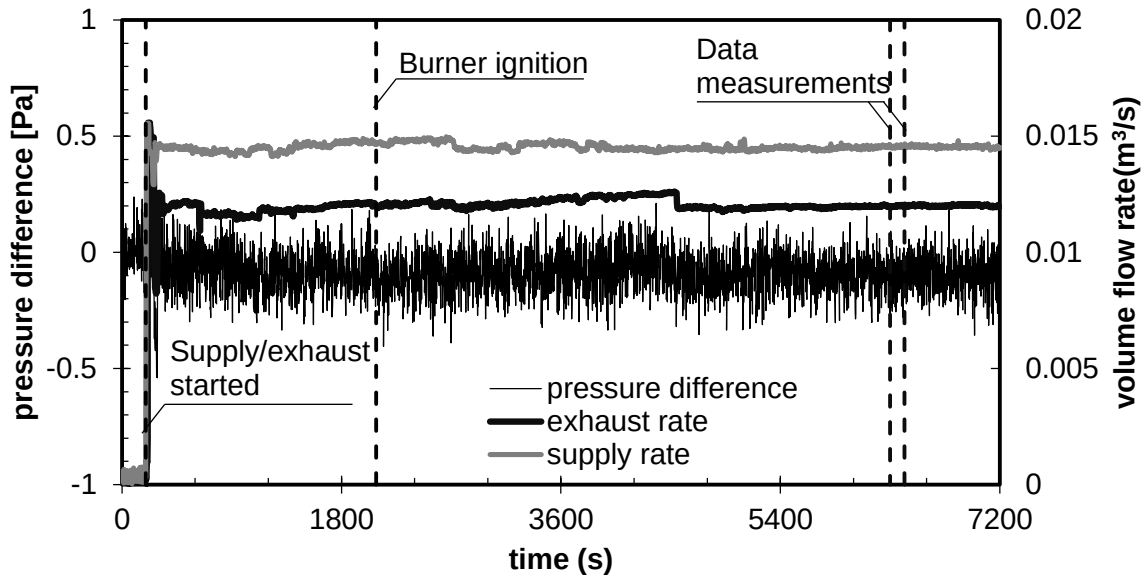
Exp. No.	supply air		exhaust smoke		smoke layer			opening	outside air	
	supply rate V_{supply} [m ³ /s]	CO ₂ conc. Y_{supply} [%]	exhaust rate V_{ex} [m ³ /s]	CO ₂ conc. Y_{ex} [%]	thick-ness H_{smoke} [m]	temp. rise above ambient ΔT [K]	CO ₂ conc. Y_{smoke} [%]	pressure difference* ΔP [Pa]	CO ₂ conc. Y_{air} [%]	temp. T_{air} [°C]
A-12	0.0145	0.065	0.0120	0.066	0.125	15.2	0.110	-0.094	0.072	14.0
A-19	0.0131	0.077	0.0103	0.077	0.129	14.7	0.098	-0.083	0.081	14.8
A-18	0.0125	0.078	0.0100	0.079	0.136	14.3	0.103	-0.063	0.083	14.9
A-8	0.0155	0.059	0.0136	0.058	0.128	13.7	0.095	-0.046	0.061	14.0
A-9	0.0140	0.073	0.0124	0.072	0.132	13.9	0.090	-0.025	0.074	14.6
A-1	0.0140	0.057	0.0142	0.060	0.129	11.6	0.085	-0.017	0.059	12.9
A-10	0.0144	0.072	0.0132	0.073	0.131	13.9	0.085	-0.016	0.075	14.7
A-17	0.0127	0.077	0.0127	0.081	0.133	14.9	0.099	0.001	0.081	14.8
A-14	0.0127	0.079	0.0141	0.090	0.129	14.8	0.104	-0.004	0.081	14.9
A-11	0.0146	0.075	0.0153	0.079	0.131	13.8	0.092	-0.004	0.076	14.6
A-4	0.0148	0.059	0.0150	0.061	0.131	13.9	0.097	0.003	0.063	15.0
A-15	0.0136	0.065	0.0149	0.073	0.126	14.5	0.105	0.023	0.068	14.0
A-5	0.0132	0.080	0.0149	0.091	0.130	13.4	0.099	0.029	0.083	15.7
A-13	0.0125	0.078	0.0143	0.093	0.126	14.1	0.102	0.031	0.080	14.6
A-6	0.0126	0.090	0.0148	0.104	0.133	13.4	0.094	0.040	0.092	15.9
A-16	0.0126	0.074	0.0149	0.090	0.126	14.4	0.107	0.057	0.078	14.6
A-2	0.0125	0.066	0.0151	0.080	0.126	11.0	0.081	0.081	0.067	13.5
A-3	0.0122	0.066	0.0152	0.082	0.124	10.4	0.078	0.101	0.066	13.5
A-7	0.0113	0.095	0.0145	0.115	0.125	13.3	0.095	0.111	0.093	16.3

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

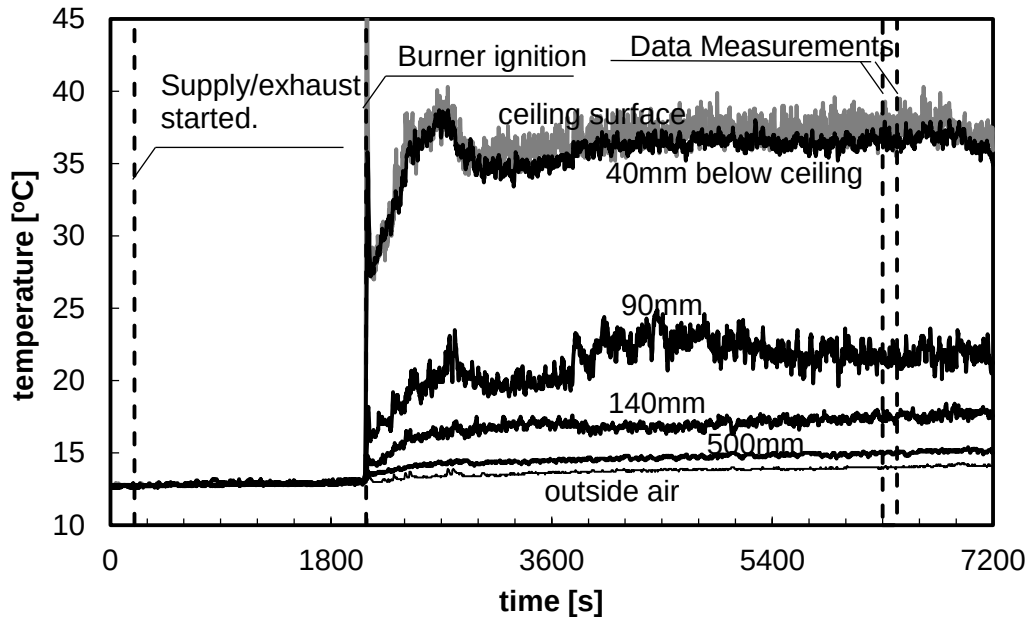
3.1.2 An example of measured results

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.



a) air supply rate, smoke exhaust rate and pressure difference across opening



b) temperatures at thermocouples tree

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

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

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

$$H_{smoke} = 0.125 \text{ m}, \quad (7)$$

$$T_{smoke} = 29.2 \text{ }^{\circ}\text{C}. \quad (8)$$

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

$$Y_{smoke} = 0.182 \% \quad (9)$$

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

$$m_{smoke} = \frac{353}{29.2 + 273.2} \frac{0.066 - 0.065}{0.182 - 0.066} \times 0.145 = 0.00015 \text{ kg/s}, \quad (10)$$

$$m_{air} = \frac{353}{13.9 + 273.2} \left(\frac{0.182 - 0.065}{0.182 - 0.066} \times 0.145 - 0.0122 \right) = 0.0308 \text{ kg/s}. \quad (11)$$

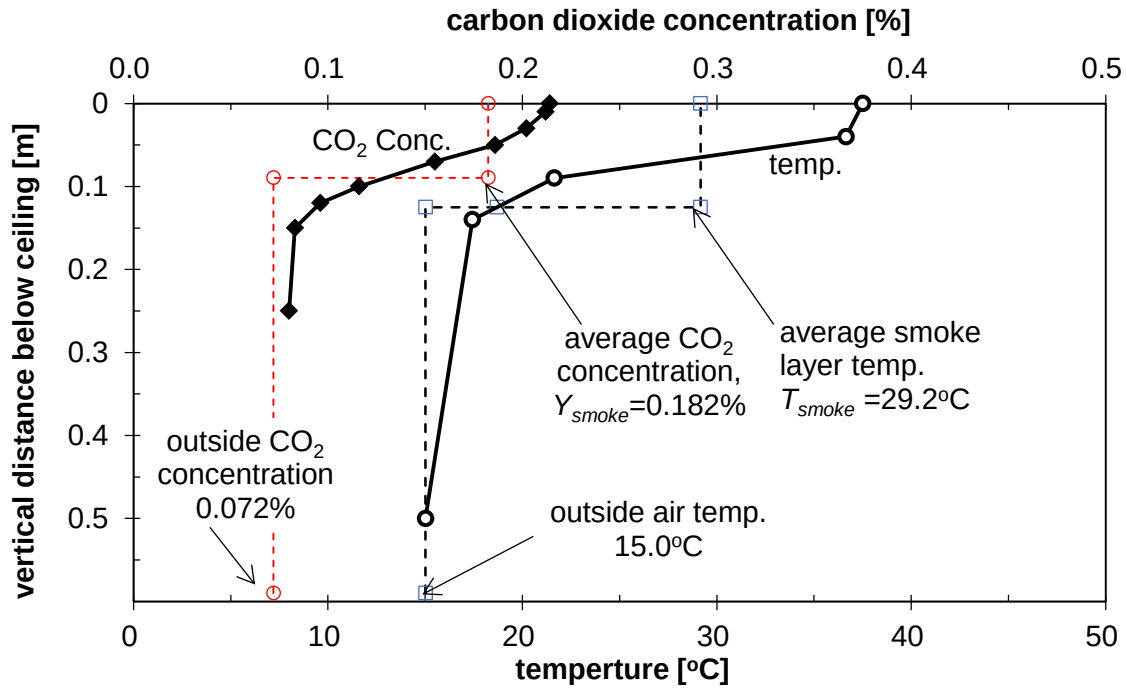


Fig. 6 Vertical profiles of temperature and CO₂ concentration at steady state (6,300-6,420 seconds)

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 0.040 Pa 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.

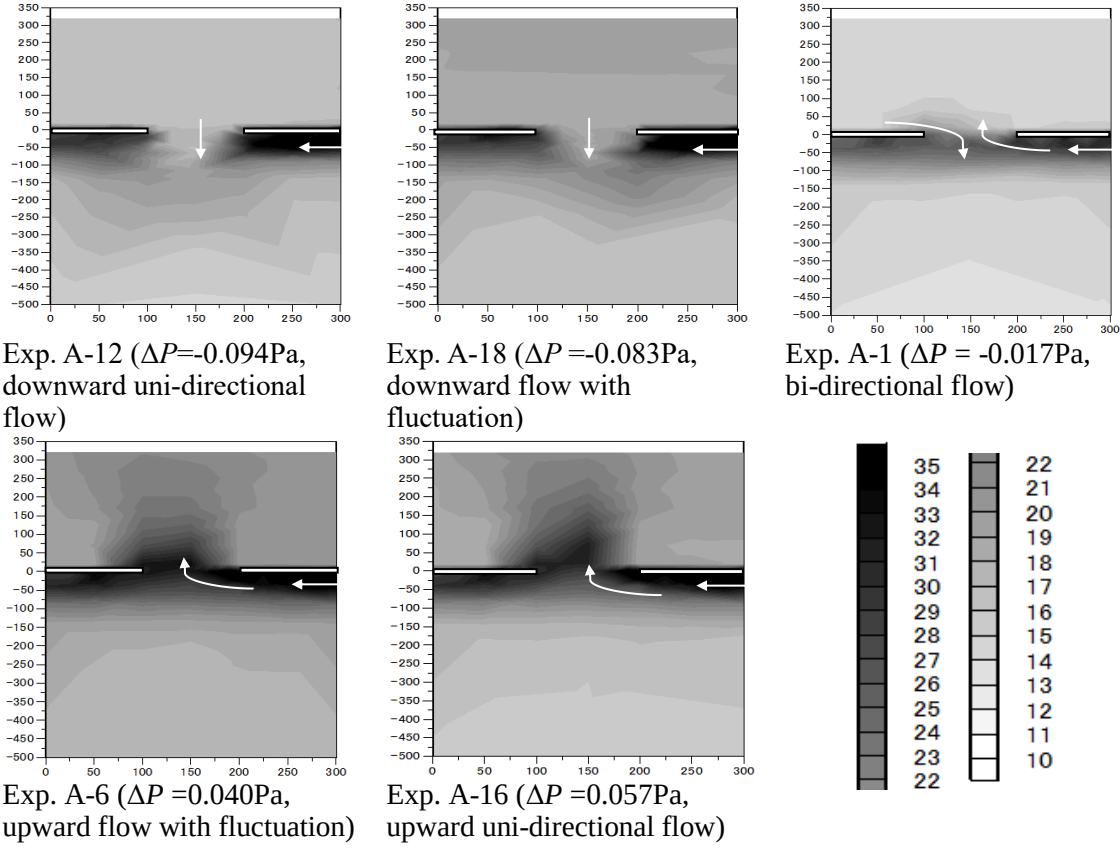


Fig. 7 Typical flow patterns and temperature contours in Series A

3.1.4 Mass flow rates

Using the measured CO₂ 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],

$$\Delta p_{flood} = 0.9708 \Delta \rho g D \left(1 + \frac{1}{2} \frac{\Delta \rho}{\rho_{ave}} \right) \exp(1.1072 \frac{\Delta \rho}{\rho_{ave}}) = 0.044 \text{ Pa} , \quad (12)$$

where the average density of smoke and air was calculated by

$$\rho_{ave} = 353 / \{ (T_{smoke} + T_{air}) / 2 \} = 353 / 301 = 1.20 \text{ kg/m}^3 . \quad (13)$$

Table 2 Measured mass flow rates in Series A

Exp. No.	pressure difference ΔP [Pa]	flow rate		flow pattern*	critical pressure difference for
		smoke (upward)	air (downward)		

		[kg/s]	[kg/s]		flooding, ΔP_{flood} [Pa]
A-12	-0.094	0.00015	-0.00308	DU	-0.088
A-19	-0.083	0.00000	-0.00321	DF	-
A-18	-0.063	0.00014	-0.00306		-
A-8	-0.046	-0.00018	-0.00199		-
A-9	-0.025	-0.00018	-0.00165		-
A-1	-0.017	0.00059	-0.00024	B	-
A-10	-0.016	0.00019	-0.00164	UF	-
A-17	0.001	0.00060	-0.00051	B	-
A-14	-0.004	0.00171	0.00000	UF	-
A-11	-0.004	0.00077	0.00009	B	-
A-4	0.003	0.00035	-0.00015		-
A-15	0.023	0.00128	0.00027	UF	-
A-5	0.029	0.00185	0.00005		-
A-13	0.031	0.00243	-0.00034		-
A-6	0.040	0.00247	0.00001		0.049
A-16	0.057	0.00241	0.00014	UU	-
A-2	0.081	0.00290	0.00007		-
A-3	0.101	0.00361	-0.00021		-
A-7	0.111	0.00344	0.00014		-

* DU:Downward Uni-directional flow, DF:Downward Fluctuating flow, B:Bi-directional flow, UF:Upward Fluctuating flow, UU:Upward Uni-directional flow

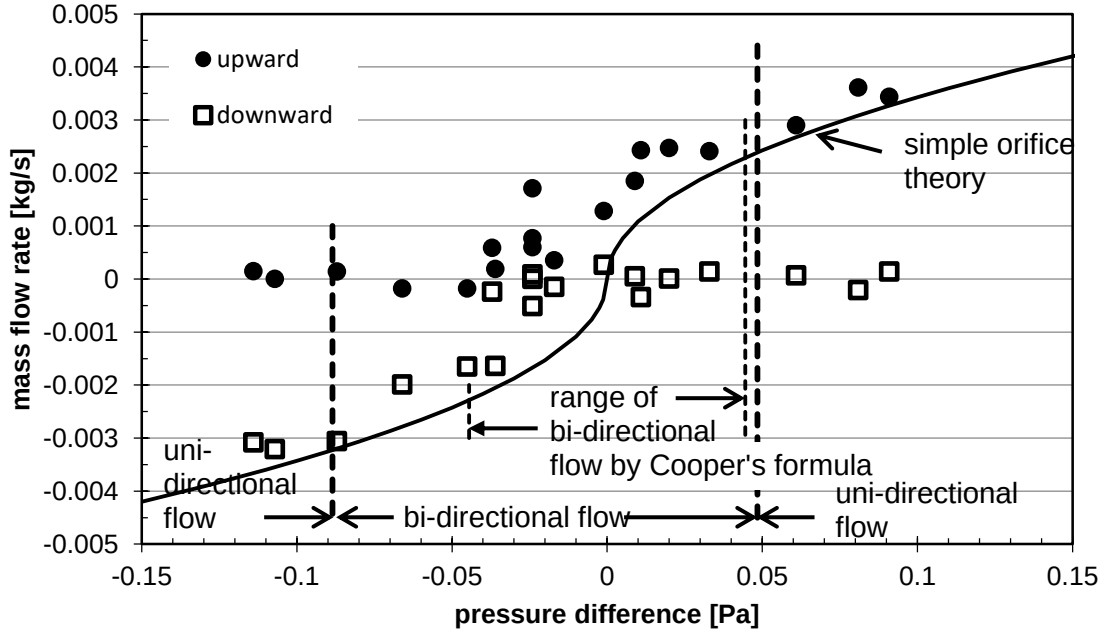


Fig. 8 Measured volumetric flow rates in Series A

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

$$m = \alpha A \sqrt{2 \rho_{ave} \Delta P} = 0.7 \times 0.01 \sqrt{2 \times 1.20 \times \Delta P} = 0.0108 \sqrt{\Delta P} . \quad (14)$$

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 -0.017Pa. 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 28K 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, $(\rho_s - \rho_a) g H_{smoke}$ [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, $\Delta \rho g H_{smoke}$. 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

$$\Pi_{flood} \equiv \frac{\Delta P_{flood}}{\Delta \rho g H_{smoke}} = \begin{cases} 0.98 & \text{(upward flooding)} \\ -0.47 & \text{(downward flooding)} \end{cases} \quad (15)$$

Table 3 Experimental Results for temperature differences 20, 25 and 30K (Series B, C, D and E)[13]

series	Exp. No.	Smoke layer		pressure difference ΔP [Pa]	Flow rate		flow pattern*	critical pressure difference for flooding ΔP_{flood} [Pa]
		thick-ness H_{smoke} [m]	temp. rise ΔT [K]		smoke (upward) m_{smoke} [m ³ /s]	air (downward) m_{air} [m ³ /s]		
B	B1	0.095	20.5	-0.11	N.A.	N.A.	DU	-
	B2	0.089	20.9	-0.088				-
	B3	0.09	21.7	-0.042				-0.024
	B4	0.094	20.5	-0.006			B	-
	B5	0.098	20.3	0.021			FD	-
	B6	0.103	18.3	0.038			B	-
	B7	0.089	18.6	0.094			FU	0.105
	B8	0.088	19.2	0.115			UU	-
	B9	0.086	19.1	0.162				-
	ave.	0.0924	19.9	-	-	-	-	-
C	C1	0.122	25.5	-0.108	N.A.	N.A.	DU	-
	C2	0.12	25.6	-0.037				-0.024
	C3	0.12	24.7	-0.011			B	-
	C4	0.119	26.0	0.002			FD	-
	C5	0.12	25.5	0.019			B	-
	C6	0.118	24.0	0.069			FU	-
	C7	0.114	24.0	0.104				0.115

	C8	0.113	23.5	0.126			UU	
	ave	0.118	24.9	-	-	-	-	-
D	D1	0.124	25.6	-0.103	N.A.	N.A.	DU	-0.0815
	D2	0.113	30.6	-0.06			DF	
	D3	0.115	30.1	-0.02				
	D4	0.121	28.3	-0.005			B	-
	D5	0.122	29.4	0.006				-
	D6	0.119	27.8	0.04			UF	-
	D7	0.114	27.8	0.057				-
	D8	0.113	27.8	0.098				-
	D9	0.111	27.7	0.105				0.108
	D10	0.108	28.0	0.111			UU	
	ave.	0.116	28.3	-	-	-	-	-
E	Y1	0.119	24.2	-0.084	0.00053	0.00122	DU	N.A.
	Y2	0.105	23.2	-0.053	0.00106	0.00007	UF	
	Y3	0.109	22.9	-0.020	0.00177	-0.00040	UU	
	Y4	0.108	23.8	-0.003	0.00162	-0.00026	UF	
	Y5	0.078	21.2	0.026	0.00195	-0.00043	UU	
	ave.	N.A.	N.A.	-	-	-	-	-

* DU:Downward Uni-directional flow, DF:Downward Fluctuating flow, B:Bi-directional flow, UF:Upward Fluctuating flow, UU:Upward Uni-directional flow

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211 Table 4 Experimental Results for temperature differences 10, 15 and 20K (Series F, G, H and I) [14]

series	Exp. No.	Smoke layer		pressure difference ΔP [Pa]	Flow rate		flow pattern*	critical pressure difference for flooding ΔP_{flood} [Pa]
		thick-ness H_{smoke} [m]	temp. rise ΔT [K]		smoke (upward) m_{smoke} [m ³ /s]	air (downward) m_{air} [m ³ /s]		
F	1-6	0.07	12.3	-0.004	0.00051	0.00134	DU	-0.002
	1-5	0.068	13.2	0	0.00082	0.00081	B	
	1-4	0.063	13.3	0	0.00085	0.00061		
	1-3	0.065	11.4	0.01	0.00109	0.00055	UF	-
	1-8	0.059	12.6	0.016	0.0019	0.00031		-
	1-2	0.068	9.1	0.02	0.00163	0.00069		-
	1-10	0.069	11.9	0.021	0.00117	0.00029	B	-
	1-9	0.058	12.5	0.025	0.00196	0.00028	UF	0.033
	1-1	0.055	9.8	0.041	0.0016	-0.00025	UU	
	1-7	0.056	11.3	0.05	0.00176	-0.00046		
	ave.	0.631	11.74	-	-	-	-	-
G	2-6	0.076	18.3	-0.01	N.A.	N.A.	DU	-0.005
	2-5	0.076	18.3	-0.001	0.00099	0.00078	B	
	2-4	0.071	20.5	0.001	0.00095	0.00076		
	2-3	0.067	21	0.042	0.00107	0.00017	-	
	2-2	0.068	16.9	0.043	0.00194	0.00039	UF	0.059
	2-1	0.063	19.1	0.075	0.00235	0.00024	UU	
	ave.	0.070	19.02	-	-	-	-	
H	3-1-1	0.108	10.7	-0.028	N.A.	N.A.	DU	-0.021
	3-1-3	0.108	10.7	-0.013			DF	
	3-1-2	0.108	10.7	-0.013			DU	-
	3-1-5	0.108	10.7	-0.008			UF	-
	3-1-6	0.108	10.7	-0.003				-

	3-1-4	0.108	10.7	0.007				-
	3-1-7	0.108	10.7	0.022				0.024
	3-1-8	0.108	10.7	0.027			UU	
	ave.	0.108	10.7	-	-	-	-	-
I	3-2-3	0.102	15	-0.016	N.A.	N.A.	DU	-0.016
	3-2-1	0.102	15	-0.016			DF	-
	3-2-2	0.102	15	-0.016			B	-
	3-2-4	0.102	15	0.004			UF	0.029
	3-2-6	0.102	15	0.024			UU	-
	3-2-7	0.102	15	0.034				-
	3-2-5	0.102	15	0.044				-
	ave.	0.102	15	-	-	-	-	-

* DU:Downward Uni-directional flow, DF:Downward Fluctuating flow, B:Bi-directional flow, UF:Upward Fluctuating flow, UU:Upward Uni-directional flow

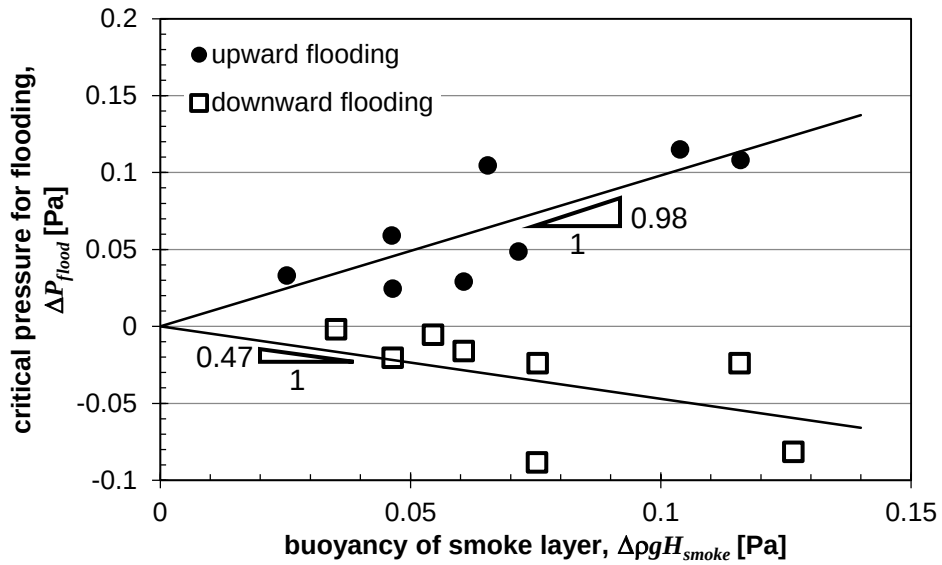


Fig. 9 Critical pressure differences for uni-directional flow

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

$$\Pi = \Delta P / \Delta \rho g H_{smoke} \quad (16)$$

$$Fr = \left(m / \rho D^2 \right) / \sqrt{2 \Delta \rho g H_{smoke} / \rho_{ave}} \quad (17)$$

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

$$Fr = 0.7 \sqrt{\Pi} \quad (18)$$

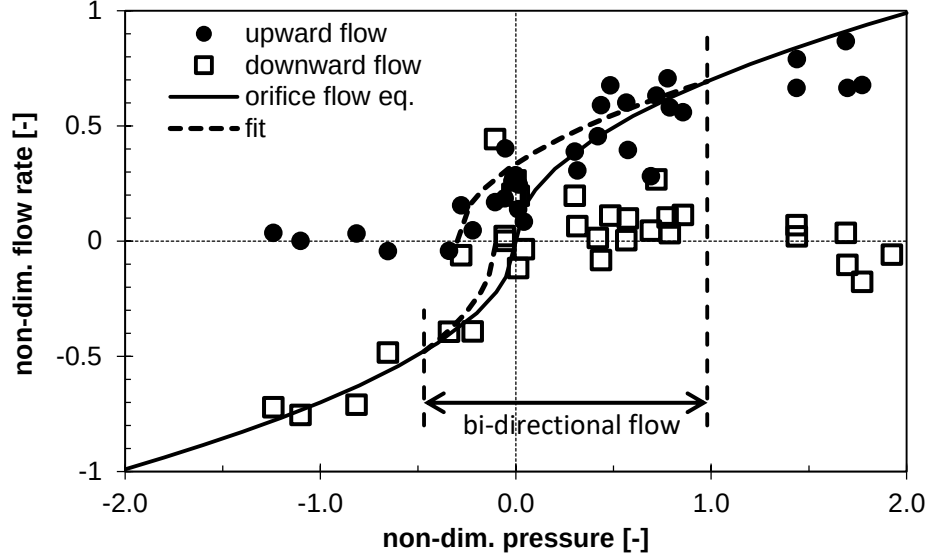


Fig. 10 non-dimensional mass flow rate as functions of non-dimensional pressure difference

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

$$Fr_{smoke} = 0.7 \times \begin{cases} 0 & (\Pi \leq -0.3) \\ \sqrt{\frac{\Pi + 0.3}{1.28}} & (-0.3 < \Pi \leq 0.98), \\ \sqrt{\Pi} & (0.98 < \Pi) \end{cases} \quad (19)$$

$$Fr_{air} = -0.7 \times \begin{cases} \sqrt{-\Pi} & (\Pi \leq -0.47) \\ \sqrt{-0.47 \frac{\Pi + 0.1}{0.37}} & (-0.47 < \Pi \leq -0.1), \\ 0 & (-0.1 < \Pi) \end{cases} \quad (20)$$

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.

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