EXPERIMENTAL STUDIES ON SMOKE CONTROL WITH MECHANICAL EXHAUST AT LOW LEVEL IN A CABIN FIRE

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ABSTRACT

Although the cabin design is widely used for providing fire safety in big and tall public transport terminals in the Far East, there are many debates on its performance. Very few experimental studies with big fires in a cabin were reported in the literature. In many applications, smoke exhaust was at low level in the cabin. The performance of such systems has to be justified. Full-scale burning tests were carried out to study smoke exhaust at low levels in a cabin fire. A cabin of length 3 m, width 4 m and height 3 m was constructed. Smoke temperature, average smoke layer height in the cabin, and velocity in the fan duct were measured with different heat release rates and heights of the ventilation opening. Eight sets of tests were carried out with results reported in this paper. For smoke exhaust at low level, the interface of smoke layer was low, usually lower than the height of the ventilation opening. The fire plume was then at the continuous flame zone. The interface of the smoke layer would be tilted. The smoke layer near the mechanical exhaust ventilation was lower than that at the opposite wall. The calculated smoke production rate would then be lower than the mechanical exhaust rate, as air would be extracted directly from the lower layer. In designing mechanical exhaust system in a cabin, the plume coefficient should be tuned up by a factor. In this paper, the mechanical exhaust rate used in cabin design at low levels would be estimated by changing the coefficient concerned. Plume correlation expression due to McCaffrey was taken as an example. Semi-empirical correlation of the flow rates of the fan in controlling smoke not to spill out was derived based on the experimental data.

KEYWORDS: Cabin fire, Smoke control, Mechanical exhaust, Low level, Smoke layer height, Height of ventilation opening, McCaffrey plume correlation, Full-scale burning test

INTRODUCTION

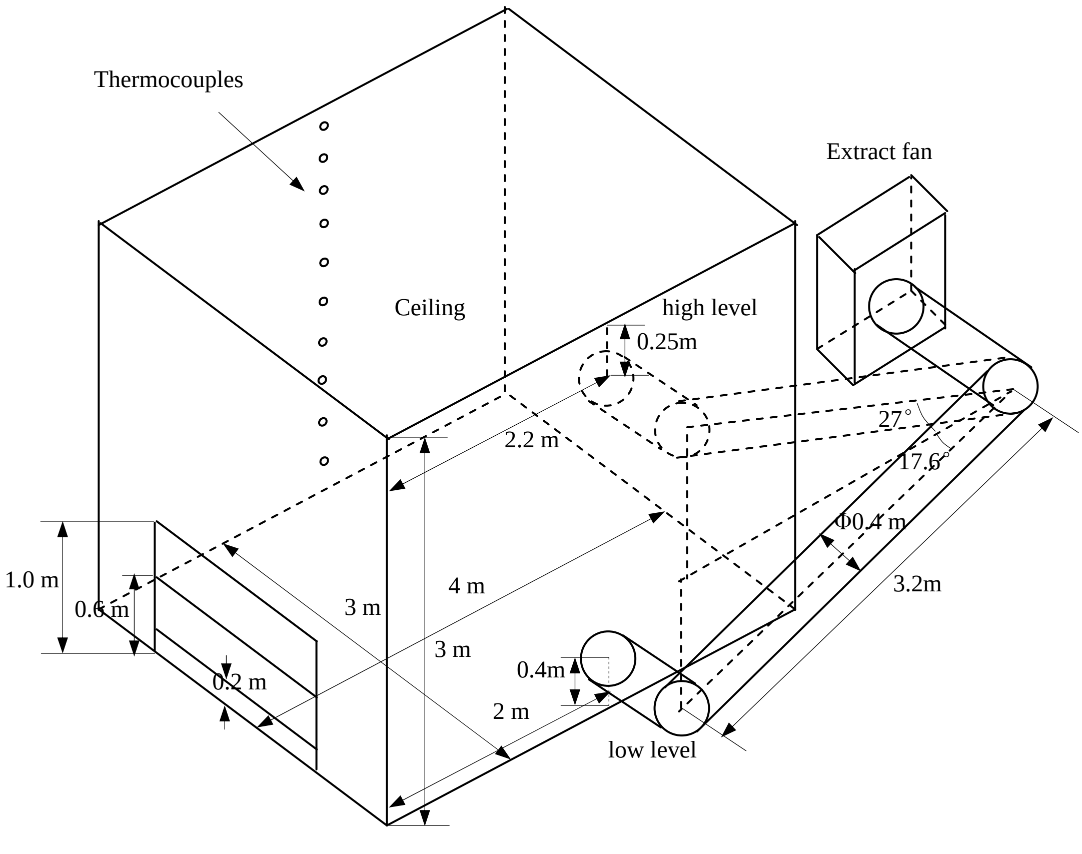
Cabin design[1-3] is commonly found in big and tall transport terminals in the Far East. It is used widely for fire safety protection in retail areas, considered to be a good design[4,5] by allowing more space allocation. The whole hall is not covered by sprinklers; only the areas with higher fire risk are protected.

A cabin fire should be controlled effectively by preventing flashover and without spreading smoke out into the large outside hall. To achieve that, there are fire detection and alarm systems, sprinkler systems, and mechanical smoke exhaust systems. Because of limitations imposed, such as retail arrangement or architectural constraints, smoke exhausts are commonly found at low levels. Very few full-scale experiments were carried out on cabin fires. Those were only focused on flashover in a cabin[6, 7], fire growth model with a small fire in a cabin[8-10], spill plume model[10] and smoke filling in an atrium due to a cabin fire[10, 11]. No systematic experimental studies on smoke mechanical exhaust at low levels in the cabin are reported.

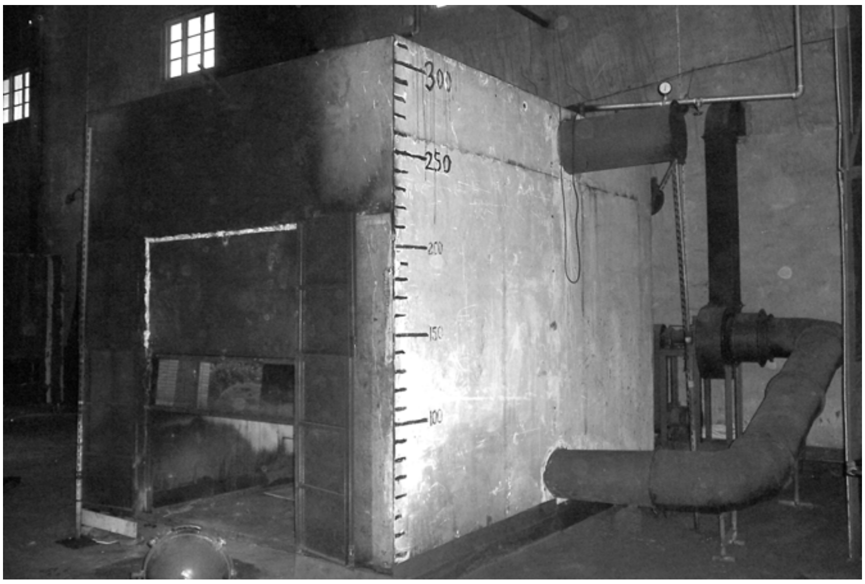
In this paper, performance of smoke exhaust system at lower levels will be discussed. Eight tests on cabin fire were carried out in a big burning hall at the State Key Laboratory of Fire Science, University of Science and Technology of China (USTC).

EXPERIMENTAL SETUP

Experiments were performed in a full-scale cabin of length 3 m, width 4 m and height 3 m as illustrated in Fig. 1. The cabin was made of steel. The roof and the walls were made of double-deck fireproof gypsum boards of 7 cm thick. The cabin model was jointly built by University of Science and Technology of China and The Hong Kong Polytechnic University. The width of the ventilation opening was kept at 1.6 m, and the height could be varied to adjust the ventilation factor, 1.0 m, 0.6 m and 0.2 m were used in the experiments.



(a) Schematic diagram



(b) Photograph

FIGURE 1. The cabin

A centrifugal water-cooling high temperature exhaust fan with adjustable flow rates was installed. The height of mechanical exhaust ventilation center was 0.4 m, the diameter was 0.4 m, connected with the fan through the ducts. The flow velocity was measured with the anemoscope inserted into the duct when the temperature in the duct returned to ambient temperature[12]. The velocity sensor used had an error of about 3%. The measurement points on the duct section[12] were illustrated in Fig. 2. The distances from measurement points to the center were 0.1 m and 0.17m. Four points were selected symmetrically in one diameter. The average flow velocity V of four measurement points (V_i, i = 1,…,4) was the flow velocity in duct. From Fig. 2, the average velocity was:

$$V=\frac{1}{4}\sum_{i=1}^{4}V_i \qquad [1]$$

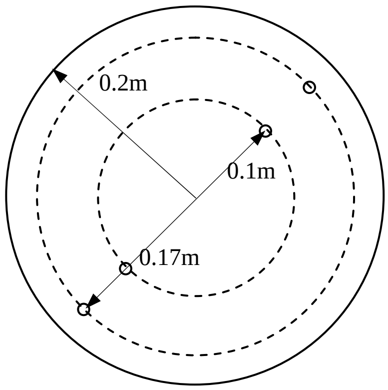


FIGURE 2. Duct section in measuring air speeds

Smoke temperature inside the cabin was measured by K-type shielded thermocouples inserted in the holes drilled on the northern cabin wall as shown in Fig. 3. Ten holes (labeled as TC1 to TC10 in Fig. 3) were spaced uniformly along a vertical line in two parts. The distances from the measurement points to the inside wall were 0.5 m. The diameter of the thermocouples was 1 mm, and the measurement error was about 3%.

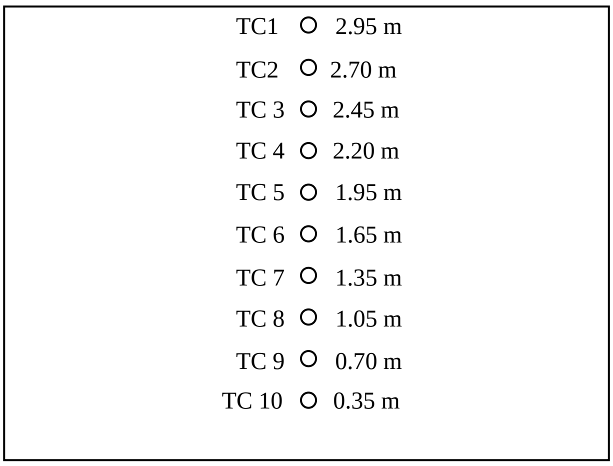


FIGURE 3. Location of thermocouples

Heat release rates (HRR) of pool fire with diesel oil were measured separately in an oxygen consumption calorimeter[13] in a room calorimeter with measurement error of 5%. Three different sizes of diesel pool fires PF1, PF2 and PF3 were considered:

- PF1 : 0.7 m by 0.7 m
- PF2 : 0.6 m by 0.6 m
- PF3 : 0.5 m by 0.5 m

The HRR for steady burning was measured to be 378 kW for PF1, 228 kW for PF2 and 164 kW for PF3.

TESTS

Eight tests labeled as Tests 1 to 8 were carried out.

Test 1: Liquid pool fire PF1 was placed at the centre of the cabin at ground level. A ventilation opening of width 1.6 m and height 1.0 m was used.

Test 2: Liquid pool fire PF2 was used with same ventilation opening as Test 1.

Test 3: Liquid pool fire PF3 was used with same ventilation opening as Test 1.

Test 4: Liquid pool fire PF1 with ventilation opening of same width 1.6 m, but height reduced to 0.6 m.

Test 5: Liquid pool fire PF2 was used with same ventilation as Test 4.

Test 6: Liquid pool fire PF3 with ventilation opening as Test 4.

Test 7: Liquid pool fire PF1 was used with ventilation opening of width 1.6 m, but height further reduced to 0.2 m.

Test 8: Liquid pool fire PF2 with same ventilation opening as Test 7.

The pool fire ranges with only one tray and the possible HRR are shown in Table 1.

TABLE 1. Experimental conditions of all tests

Test number		1	2	3	4	5	6	7	8
Pool fire	Length / m	0.7	0.6	0.5	0.7	0.6	0.5	0.7	0.6
	HRR / kW	378	228	164	378	228	164	378	228
Ventilation opening	Width / m	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
	Height / m	1.0	1.0	1.0	0.6	0.6	0.6	0.2	0.2
Ambient temperature in cabin / ^{o}C		26	29	30	31	28	30	34	34

OBSERVATIONS

Large quantities of smoke were emitted once the diesel was ignited. The upper part of the cabin was quickly filled with smoke. Upon operating the mechanical smoke exhaust fan, smoke was controlled in the cabin without spilling out. A hot smoke layer was observed, giving a two-layer structure. Though smoke was controlled in the cabin without spilling, the interface of the smoke layer was lower than the height of the ventilation opening. Air was supplied into the cabin through the ventilation opening. Smoke near the ventilation opening turned back and was prevented by the supplied air. Because of the mechanical exhaust system, the interface of smoke layer was tilted. The smoke layer height near to the mechanical exhaust was lower than the opposite smoke layer height.

For Test 1, smoke was exhausted by the mechanical ventilation system. The smoke layer height near the exhaust position was about 0.4 m. The mechanical exhaust system functioned and much air was extracted directly from the air layer by the fan. The smoke layer height on the other side was about 0.6 m. The average smoke layer height for Test 1 was about 0.5 m.

For Test 2, smoke layer height near the exhaust position was about 0.4 m. The smoke layer height on the other side was about 0.6 m. The average smoke layer height for Test 2 was about 0.5 m.

For Test 3, smoke layer height near the exhaust position was about 0.4 m. The smoke layer height on the other side was about 0.6 m. The average smoke layer height for Test 3 was about 0.5 m.

For Test 4, smoke layer height near the exhaust position was about 0.3 m. The smoke layer height on the other side was about 0.5 m. The average smoke layer height for Test 4 was about 0.4 m.

For Test 5, smoke layer height near the exhaust position was about 0.3 m. The smoke layer height on the other side was about 0.5 m. The average smoke layer height for Test 5 was about 0.4 m.

For Test 6, smoke layer height near the exhaust position was about 0.3 m. The smoke layer height on the other side was about 0.5 m. The average smoke layer height for Test 6 was about 0.4 m.

For Test 7, mechanical exhaust ventilation could not be observed, and smoke layer height near the exhaust position descended to the ground. The smoke layer height on the other side was about 0.3 m. The average smoke layer height for Test 7 was about 0.15 m.

For Test 8, smoke layer height near the exhaust position descended to the ground. The smoke layer height on the other side was about 0.3 m. The average smoke layer height for Test 8 was about 0.15 m.

The flame was tilted towards the mechanical exhaust with a lower flame height. Because the smoke layer heights were very low, the fire plumes were observed in the continuous flame zone for Tests 1 to 8.

Observations in all the tests are summarized in Table 2.

TABLE 2. Observations in all the tests

Test number	1	2	3	4	5	6	7	8
Smoke spill out?	No	No	No	No	No	No	No	No
Average smoke layer height / m	0.5	0.5	0.5	0.4	0.4	0.4	0.15	0.15
Region of plume	continu-ous flame	continu-ous flame	continu-ous flame	continu-ous flame	continu-ous flame	continu-ous flame	continu-ous flame	continu-ous flame

When the smoke layer height reached the required height, the adjustable valve of the fan was fixed. After the test ended, the anemoscope was inserted into the duct to measure the flow velocity when the temperature in the duct returned to ambient temperature. The average flow velocity in the duct was respectively 18.5 ms^{-1} for Test 1, 18.1 ms^{-1} for Test 2, 17.1 ms^{-1} for Test 3, 18.3 ms^{-1} for Test 4, 17.7 ms^{-1} for Test 5, 15.9 ms^{-1} for Test 6, 13.4 ms^{-1} for Test 7, and 11.7 ms^{-1} for Test 8.

Velocities and fan flow rates in all the tests are summarized in Table 3.

TABLE 3. Velocities and fan flow rates of all the tests

Test number	1	2	3	4	5	6	7	8
Velocity in duct / ms^{-1}	18.5	18.1	17.1	18.3	17.7	15.9	13.4	11.7
Fan flow rate / m^3s^{-1}	2.32	2.27	2.15	2.30	2.22	2.00	1.68	1.47

SMOKE TEMPERATURE

Average smoke layer temperatures in the cabin for Tests 1 to 8 are shown in Table 4. In a zone model, the temperature in the hot smoke layer was assumed to be uniform. The average temperature of the whole upper layer was estimated from the thermocouples in the upper layer. A space average was performed for the thermocouples in the upper layer, then a time average was performed during the steady burning process.

For Test 1, TC1 to TC9 were in the upper layer, and the average temperature of smoke layer at stable stage was 155 ^{o}C.

For Test 2, TC1 to TC9 were in the upper layer, and the average temperature of smoke layer at stable stage was 134 ^{o}C.

For Test 3, TC1 to TC9 were in the upper layer, and the average temperature of smoke layer at stable stage was 142 ^{o}C.

For Test 4, TC1 to TC9 were in the upper layer, and the average temperature of smoke layer at stable stage was 168 ^{o}C.

For Test 5, TC1 to TC9 were in the upper layer, and the average temperature of smoke layer at stable stage was 138 ^{o}C.

For Test 6, TC1 to TC9 were in the upper layer, and the average temperature of smoke layer at stable stage was 146 ^{o}C.

For Test 7, TC1 to TC10 were in the upper layer, but TC10 was near the interface of the smoke layer, so TC1 to TC9 were selected to calculate the average temperature of the smoke layer, and the average temperature of smoke layer at stable stage was 191 ^{o}C.

For Test 8, TC1 to TC10 were in the upper layer, but TC10 was near the interface of the smoke layer, so TC1 to TC9 were selected to calculate the average temperature of the smoke layer, and the average temperature of smoke layer at stable stage was 168^{o}C.

Average temperature and density of smoke layer in all the tests are summarized in Table 4.

TABLE 4. Average temperature and density of smoke layer in all the tests

Test number	1	2	3	4	5	6	7	8
Average temperature of smoke layer / ^{o}C	155	134	142	168	138	146	191	168
Average density of smoke layer / kgm^{-3}	0.82	0.87	0.85	0.80	0.86	0.84	0.76	0.80

DISCUSSIONS

A two-layer zone model was used to analyze the smoke control by mechanical exhaust at low levels in a cabin fire[14]. There were two layers: the upper hot smoke layer and the lower air layer. Smoke was controlled not to be spilling out from the cabin; mechanical exhaust at low levels in a cabin fire was illustrated in Fig. 4.

Mass conservation gives:

Upper hot smoke layer:

$$\dot{m}_s = \dot{m}_p + \dot{m}_c - \dot{m}_{es} \qquad [2]$$

Lower air layer:

$$\dot{m}_a = \dot{m}_i - \dot{m}_p - \dot{m}_c - \dot{m}_{ea} \qquad [3]$$

where $\dot{m}_s$ is the net mass rate of the upper hot smoke layer, $\dot{m}_p$ is the mass flow rate of plume into the upper hot smoke layer (namely, the mass flow rate of smoke produced), $\dot{m}_c$ is the mass exchange rate at the smoke layer interface mixed with air, $\dot{m}_{es}$ is the mass rate extracting smoke from the upper smoke layer, $\dot{m}_a$ is the net mass rate of the lower air layer, and $\dot{m}_{ea}$ is the mass rate extracting air directly from the lower air layer.

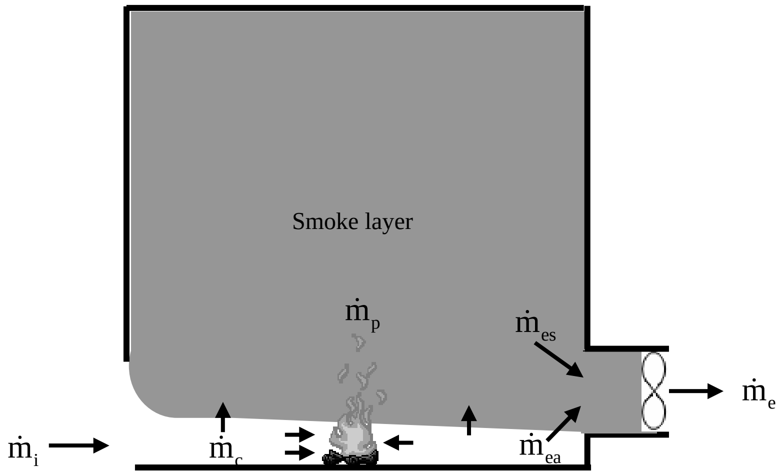


FIGURE 4. Mechanical smoke exhaust at low level in a cabin fire

The total mechanical exhaust rate $\dot{m}_e$ is:

$$\dot{m}_e = \dot{m}_{es} + \dot{m}_{ea} \qquad [4]$$

When the mass rate of entering the upper layer is balanced by the mass rate of leaving the upper layer, equation [2] becomes:

$$\dot{m}_p + \dot{m}_c - \dot{m}_{es} = 0 \qquad [5]$$

Equation [3] is:

$$\dot{m}_i - \dot{m}_p - \dot{m}_c - \dot{m}_{ea} = 0 \quad [6]$$

Summing up equations [5] and [6] gives:

$$\dot{m}_i = \dot{m}_e \quad [7]$$

In this way, the hot smoke interface is tilted but kept at a height. The height of the interface was usually observed to be lower than the height of the ventilation opening.

As the smoke temperature in the cabin is much higher than the ambient air temperature, the mass exchange at the smoke layer interface is weak, and $\dot{m}_c$ can be ignored. Equations [5] and [6] are now simplified as:

$$\dot{m}_p = \dot{m}_{es} < \dot{m}_e \quad [8]$$

$$\dot{m}_p = \dot{m}_i - \dot{m}_{ea} < \dot{m}_i \quad [9]$$

So $\dot{m}_p$ is much lower than $\dot{m}_e$ and $\dot{m}_i$, and

$$\dot{m}_e = \dot{m}_i = \dot{m}_p + \dot{m}_{ea} \quad [10]$$

The calculated smoke production rate would be much lower than the required mechanical exhaust rate, because there is much air extracting from the lower air layer directly with rate $\dot{m}_{ea}$.

In designing mechanical exhaust system, a coefficient C can be used to replace $\dot{m}_{ea}$, i.e.:

$$\dot{m}_e = \dot{m}_i = C\dot{m}_p \quad [11]$$

$\dot{m}_e$ can be calculated from the flow rate of fan $\dot{V}_e$:

$$\dot{m}_e = \rho_s \dot{V}_e \quad [12]$$

where ρ_s is the average density of hot smoke by taking smoke as ideal gas.

This can be simplified as:

$$\dot{m}_e = \frac{1.29 \times 273.6}{T_s + 273.6} vA_e \quad [13]$$

where T_s is the average temperature of hot smoke measured with the thermocouples set in the cabin, v is the measured average flow velocity in the fan duct and A_e is the area of the duct section.

It was assumed that only smoke was extracted by the fan.

There were many studies reported in the literature on calculating $\dot{m}_p$, which can be expressed as a function of the heat release rate $\dot{Q}$ and smoke layer height Z:

$$\dot{m}_p = f\left(Z, \dot{Q}\right) \quad [14]$$

Based on equations [11] to [14],

$$\dot{m}_e = C\dot{m}_p = Cf\left(Z, \dot{Q}\right)$$

$$\dot{V}_e = \dot{m}_e/\rho_s = Cf\left(Z, \dot{Q}\right) / \frac{1.29 \times 273.6}{T_s + 273.6} \quad [15]$$

The fire plume is observed to have three zones: the continuous flame zone, the intermittent flame zone and the buoyant plume zone. The plume correlation by McCaffrey[15] was selected to calculate the mass flow rate of plume.

- Zone I : Continuous flame :

$$\dot{m}_p = 0.011Z^{0.566}\dot{Q}^{0.7736} \quad \text{for} \quad 0.00 \le \frac{z}{\dot{Q}^{2/5}} < 0.08 \quad [16]$$

- Zone II : Intermittent flame :

$$\dot{m}_p = 0.026Z^{0.909}\dot{Q}^{0.6364} \quad \text{for} \quad 0.08 \le \frac{Z}{\dot{Q}^{2/5}} < 0.20 \quad [17]$$

- Zone III : Buoyant plume :

$$\dot{m}_p = 0.124Z^{1.895}\dot{Q}^{0.242} \quad \text{for} \quad 0.20 \le \frac{Z}{\dot{Q}^{2/5}} \quad [18]$$

DATA ANALYSIS

Experimental results of all the tests are summarized in Table 5.

TABLE 5. Experimental results in all the tests

Test number	1	2	3	4	5	6	7	8
Mechanical exhaust rate / kgs^{-1}	1.91	1.97	1.83	1.84	1.91	1.68	1.28	1.18
Mass flow rate of plume with McCaffrey plume correlation / kgs^{-1}	0.73	0.50	0.38	0.65	0.44	0.34	0.37	0.25
Coefficient C	2.61	3.97	4.75	2.85	4.37	4.97	3.45	4.69

As shown in Table 5, the calculation results of the McCaffrey plume correlation were much lower than the experimental data. The required flow rate with mechanical exhaust at low levels was high.

For all the tests, the fire plumes were in the continuous flame zone. The coefficient C_I was:

$$C_I = \frac{\sum_{i=1}^{8} C_i}{8} = 3.96 \qquad [19]$$

Based on equation [19], to ensure that smoke is not spilling out by smoke exhaust design at low levels of a cabin, the mechanical exhaust rate has to be calculated in the continuous flame zone (I) of McCaffrey plume correlation:

$$\dot{m}_e = 0.044 Z^{0.566} \dot{Q}^{0.7736} \qquad [20]$$

Based on equation [15], the semi-empirical correlation of the flow rate of the fan controlling the smoke not spilling from the cabin at low level with the heat release rate and smoke layer height was obtained. The flow rate of the fan could be designed as:

$$\dot{V}_e = 0.044 Z^{0.566} \dot{Q}^{0.7736} / \frac{1.29 \times 273.6}{T_s + 273.6} \qquad [21]$$

If the average smoke temperature based on experimental data was used to replace T_s,

$$T_I = \frac{\sum_{i=1}^{8} T_i}{8} = 155$$

Equation [21] could be changed to:

$$\dot{V}_e = 0.053 Z^{0.566} \dot{Q}^{0.7736} \qquad [22]$$

CONCLUSIONS

The following conclusions can be drawn.

- When the smoke was controlled in the cabin without spilling with the mechanical exhaust at low levels, the interface of smoke layer was low, usually lower than the height of the ventilation opening, and the fire plume was usually in the continuous flame zone. The interface of smoke layer was tilted, and the smoke layer height near the exhaust position was lower than the opposite smoke layer height. The flame tilted greatly towards the mechanical exhaust ventilation, and the flame height decreased.

- Following a simple analysis, the calculated smoke production rate is lower than the practical required mechanical exhaust rate. This is because of the air extracting directly from the lower air layer.

- In designing mechanical exhaust system for this configuration, a coefficient C has to be used to replace $\dot{m}_{ea}$. When the fire plume was in the continuous flame zone, C_I was 3.96.

- The mechanical exhaust rate used in cabin design with smoke exhaust at low level was calculated by using the continuous flame zone (I) of McCaffrey plume correlation given by equation [20].

- The semi-empirical correlation of the flow rate of the fan controlling the smoke not to be spilling out from the cabin at low level with the heat release rate and smoke layer height was obtained. The flow rate of fan for the continuous flame zone (I) is given by equation [21].

- If the average smoke temperature based on experimental data was used to replace T_s, the semi-experiential correlation of the flow rate of the fan at the continuous flame zone (I) could be changed to equation [22].

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REFERENCES

1. Law, M., "Fire and Smoke Models – Their Use on the Design of Some Large Buildings", ASHRAE Transactions, 96: 1, 963-971, 1990.
2. Chow, W.K., "On the Cabin Fire Safety Design Concept in the New Hong Kong Airport Terminal Building", Journal of Fire Sciences, 15: 4, 404-423, 1997.
3. Chow, W.K., "A Preliminary Study on the Fire Protection Aspects of the New Airport Terminal Building", Journal of Applied Fire Science, 6: 4, 327-338, 1997.
4. Beever, P., "On the Cabins Fire Safety Design Concept in the New Hong Kong Airport Terminal Building", Journal of Fire Sciences, 16: 3, 151-158, 1998.
5. Jones, J.C., "A Contribution to the Discussion of the Cabins Fire Safety Design Concept", Journal of Fire Sciences, 16: 6, 410-413, 1998.
6. Chow, W.K., Zou, G.W., Dong, H. and Gao, Y., "Necessity of Carrying out Full-scale Burning Tests for Post-flashover Retail Shop Fires", International Journal on Engineering Performance-Based Fire Codes, 5: 1, 20-27, 2003.
7. Chow, W.K. and Kui, Q., "Time to Flashover for Fires in a Bare Cabin with Smoke Extraction System", Architectural Science Review, 44: 2, 115-125, 2001.
8. Shi, C.L., Li, Y.Z. and Huo, R., "Modeling and Experimental Studies on Mechanical Exhaust in Compartment Fire", Journal of Combustion Science and Technology, 9: 6, 546-550, 2003.
9. Shi, C.L., Li, Y.Z., Huo, R., Yao, B., Chow, W.K. and Fong, N.K., "Mechanical Smoke Exhaust for Small Retailing Shop Fires", International Journal of Thermal Sciences, 44: 2, 477-490, 2005.
10. Shi, C.L., Study on Enclosure Fire Growth and Smoke Movement in Large Space Buildings, University of Science and Technology of China, Hefei, China, 2005.
11. Huo, R., Jin, X.H., Chow, W.K. and Fong, N.K., "Experimental Studies on Natural Smoke Filling in Atrium due to a Shop Fire", Building and Environment, 40: 9, 1185-1193, 2005.
12. Yi, L., Huo, R., Wang, H.B. and Wan, Y.T., "Experimental Study on the Flow Rate Measurement of High-power Fans", Fire Safety Science, 10: 4, 227-231, 2001.
13. Yi, L., Study on Smoke Movement and Management in Atrium Buildings, University of Science and Technology of China, Hefei, China, 2005.
14. Quintiere, J.G., "Fundamentals of Enclosure Fire Zone Models", Journal of Fire Protection Engineering, 1:3, 99-119, 1989.
15. McCaffrey, B.J., "Momentum Implications for Buoyant Diffusion Flames", Combustion and Flame, 52:2, 149-167, 1983.