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Natural smoke filling in atrium with liquid pool fires up to 1.6 MW

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Abstract

Experimental studies on natural smoke filling in an atrium induced by a liquid pool fire up to 1.6 MW were carried out. The new full-scale burning facility, the PolyU/USTC Atrium constructed at Hefei in China, was used. Five sets of hot smoke tests with diesel pool fires of 2 × 2 m placed on the floor were carried out. All openings were closed, except leaving a small vertical vent of 0.2 m high for supplying fresh air. Transient variations on the mass of the burning fuel, the vertical temperature distributions and the smoke layer interface heights were measured. Results compiled from the tests were compared with those predicted by a smoke filling model developed from plume equations; the NFPA smoke filling equation; and a model developed by Tanaka and co-workers.

1. Introduction

A full-scale burning facility, the PolyU/USTC Atrium, was constructed for studying experimentally [e.g. 1–8] the atrium smoke movement. Results would be applied in determining useful design parameters and evaluating the performance of smoke management systems. This is a 20-year joint project between The Hong Kong Polytechnic University (PolyU) and the University of Science and Technology of China (USTC). The facility was located at the campus of the USTC at Hefei, with an outer dimension of 27.6 m long, 18.1 m wide and 30.6 m high, and an inner dimension of 22.4 m long, 11.9 m wide and 27 m high.

The first phase of the study is of five years duration [1]. Smoke filling, natural ventilation, smoke extraction system, sprinklers on high headroom atrium and fire detection systems will be studied. Note that very few experimental data [e.g. 9–13] on atrium smoke movement are available in the literature. Therefore, the results achieved from this testing facility are useful to tune up parameters in design equations [14–16], such as the NFPA equation [16] on a smoke filling process; and to validate fire models for predicting the fire environment. These activities will be very helpful in implementing engineering performance-based fire codes [17] in urging the Authority to accept the new concept rather than following the old building codes.

At the first stage of the study, experimental studies on natural smoke filling in the atrium due to a diesel pool fire placed at the floor level were reported. Forty hot smoke tests [e.g. 18,19] were performed with two pool fires of diameters 0.6 and 1.0 m, and heat release rates up to 650 kW [5]. Since the fire was very small, the temperature rise of the atrium air was very small. Another five tests of a bigger fire of 1.2 m diameter [6] were carried out, but the values of the temperature rise of the atrium air were still small. These tests are only useful in demonstrating the smoke filling process in atria.

Five hot smoke tests with liquid diesel pool fires of size 2 × 2 m and heat release rates up to 1.6 MW were carried out with the details reported in this paper.

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Nomenclature

A	cross-sectional area of the atrium, m^2
c_p	specific heat of air at constant pressure, kJ kg^{-1} K^{-1}
g	acceleration due to gravity, m s^{-2}
h	smoke interface height in the atrium, m
h_n	smoke layer interface height normalized as a percentage of ceiling height, %
h_s	smoke interface height at the transition into steady burning fire, m
H	height of the atrium, m
k_1	parameter in plume model
m_f	fuel mass, kg
Q	heat release rate of the fire, kW
Q_0	heat release rate of fire at steady burning period, kW
T_{av}	average smoke temperature rise, °C
T_{max}	maximum smoke temperature rise, °C
T_0	ambient temperature, °C
t	time, s
t_{av}	time to reaching average smoke temperature, s
t_{fa}	time at which smoke layer reached the floors
t_s	transition time from t^2-fire to steady burning fire, s
t_B	burning time of the fire, s
t_5	time at which smoke layer descended to 5 m down the ceiling, s
t_{10}	time at which smoke layer descended to 10 m down the ceiling, s
t_{15}	time at which smoke layer descended to 15 m down the ceiling, s
t_{20}	time at which smoke layer descended to 20 m down the ceiling, s
t_{25}	time at which smoke layer descended to 25 m down the ceiling, s
t_{50}	time taken to fill 50% of atrium with smoke
t_{80}	time taken to fill 80% of atrium with smoke

Greek symbols

α	growth factor of unsteady t^2-fires, kW s^{-2}
ρ_0	air density, kg m^{-3}

Subscripts

0	values of ambient air.

Further, measured data were compared with a smoke filling model developed earlier, the NFPA equation [16], and the calculation procedure prepared by Tanaka and Yamana [9] and Yamana and Tanaka [10].

2. Experiments

The geometry of the PolyU/USTC Atrium and the experimental arrangements are shown in Fig. 1 with details explained elsewhere [5,6]. All the ceiling vents and side windows of the atrium were closed, but leaving a vertical gap of 20 cm high at the bottom of the wall.

Five sets of hot smoke tests were performed by setting up a diesel pool fire at the centre of the atrium floor. The following three main quantities were measured:

- transient mass of the burning fuel;
- transient vertical temperature distributions;
- descending time of the smoke layer.

Diesel was put into four square trays of size 1 × 1 m to give a pool fire of 2 × 2 m as shown in Fig. 2. A weighting system with six sensors was developed for measuring transient fuel mass up to 60 kg in one of the trays. Since the mass of only one tray was measured, calibration had been made so that the total weight of the fuel would be four times the weight recorded by the weighting system. Experimental details on the preliminary trial runs were reported elsewhere [7,8] and will not be repeated here.

The values of the smoke temperature rise in the experiments were measured by a rack of 20 type K thermocouples labelled from TA1 to TA20.

The smoke layer interface heights were inspected visually according to NFPA 92B [16] on vertical smoke density distribution. The time at which the smoke layer descended to 5 m down the ceiling t_5; 10 m down the ceiling t_{10}; 15 m down the ceiling t_{15}; 20 m down the ceiling t_{20}; 25 m down the ceiling t_{25}; and on reaching the floor t_{fa}, were recorded.

The smoke layer interface height h was expressed as a percentage h_n of the ceiling height H as:

$$h_n = (h/H) \times 100\% \quad (1)$$

Values of h were also checked by measuring the vertical distribution of the temperature. Since a sharp change was not observed in the measured vertical temperature curves, the N-percentage rule proposed [20,21] was applied to identify the positions of the smoke layer interface.

In the experiment, thermal radiation emitted from the fire was very strong and people had to stay at least 5 m away. When the smoke descended to the floor, the black smoke became so thick that the fire was invisible from the inspection room adjacent to the atrium.

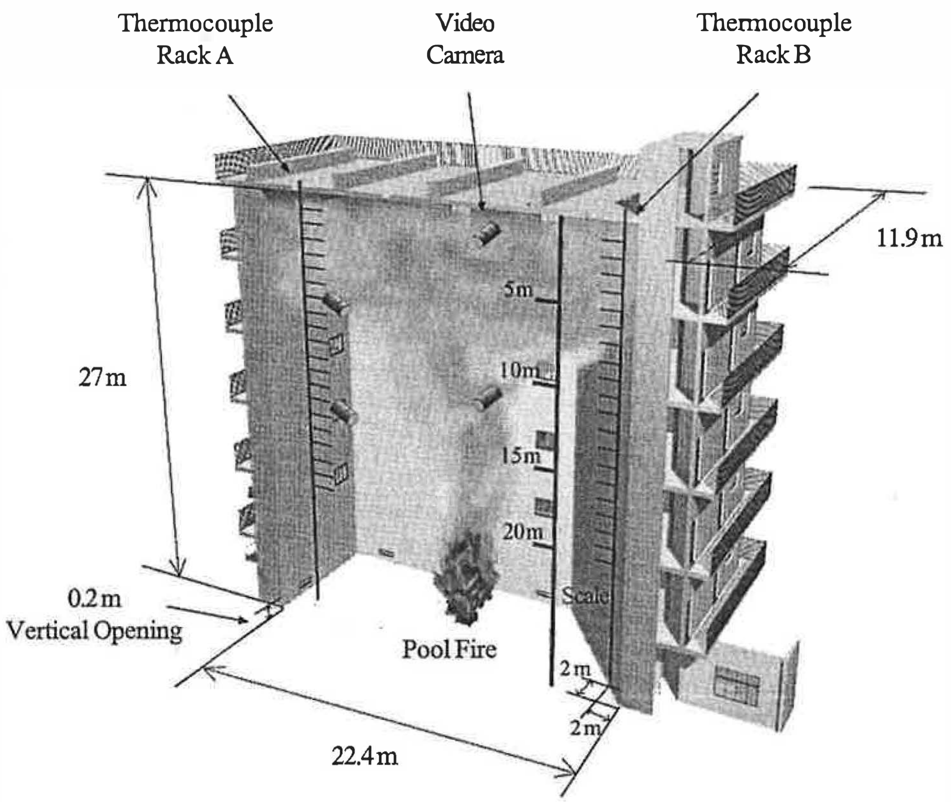

Fig. 1. PolyU/USTC Atrium.

3. Results

The heat release rates of the fire were estimated from the transient mass of the fuel measured by the weighting system by taking the heat of combustion of diesel to be 42,000 kJ kg^{-1}. The mass loss rate and the heat release rate curves of the fuel are shown in Fig. 3. It is observed from previous experiments that the heat release rates Q (in kW) of the pool fires were very close to an unsteady t^2-fire [3,7,8] at the beginning, then as a steady burning fire after time t_s:

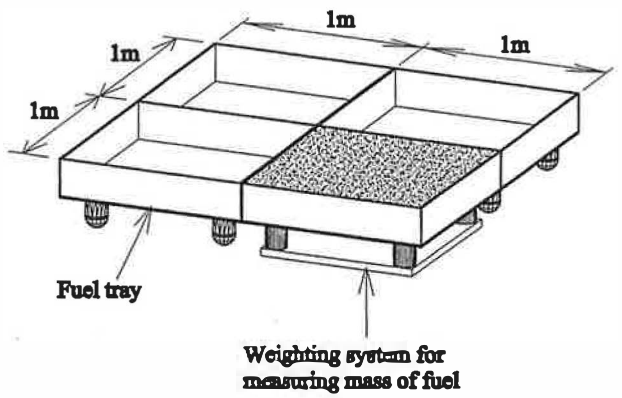

Fig. 2. Liquid pool fire.

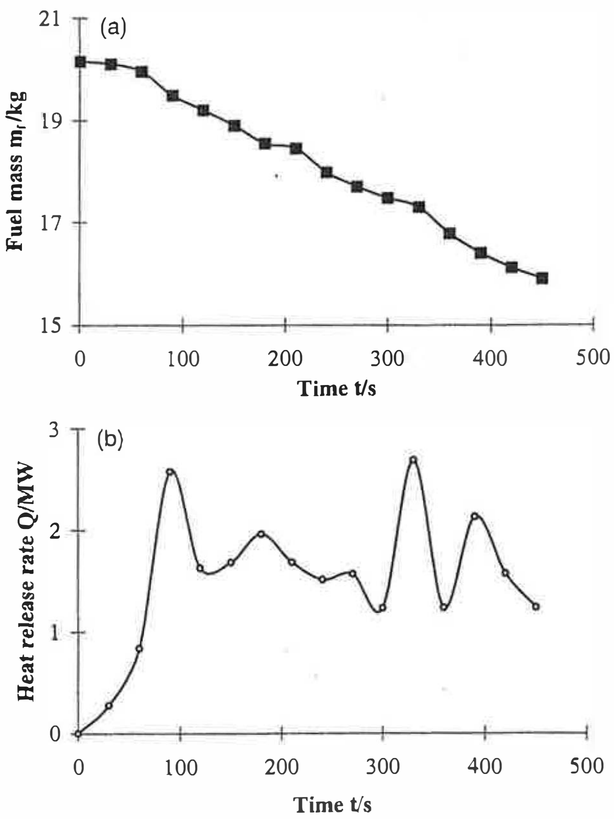

Fig. 3. Mass loss rate and heat release rate of the pool fire.

Table 1
Summary of results

Test	Mass of diesel in the weighted tray m_f/kg	Burning time t_B/s	Time of reaching steady burning t_s/s	Average HRR during steady burning Q_0/MW	Growth factor α/ kW s^{-2}	Ambient temperature T_0/°C	Maximum smoke temperature T_{max}/°C	Average smoke temperature T_{av}/°C	Time taken to reach T_{av} t_{av}/s
1	5.7	780	100	1.56	0.156	23	44	40	165
2	5.2	720	90	1.6	0.196	24	43	41	170
3	5.4	600	100	1.84	0.184	24	42	40	180
4	4.2	525	85	1.68	0.232	22	45	38	170
5	5.8	810	95	1.64	0.180	22	43	39	175
Average	–	–	94	1.66	0.1896	–	43.4	40	172

$$Q = \begin{cases} \alpha t^2 & t < t_s \\ Q_0 & t \geq t_s \end{cases} \tag{2}$$

where α is the growth factor, Q_0 is the heat release rate during steady burning, and t_s is:

$$t_s = \left(\frac{Q_0}{\alpha}\right)^{1/2} \tag{3}$$

Note that a "t^2" approximation [16] was used in the literature for describing the heat release rate of accidental open flaming fires. A t^2-fire has a burning rate proportional to the square of the time. In this way, the rate of fire growth can be classified by the growth factor as "slow", "medium", "fast" and "ultra-fast". This assumption has been verified experimentally to be good enough for providing reasonable design decisions.

Results on Q_0, α and t_s together with the fuel mass m_f, and the burning time t_B are summarized in Table 1.

A large volume of data from the thermocouples was collected in the tests. Typical results on the smoke temperature rise for the 20 measuring positions are shown in Table 2. The maximum smoke temperature rise T_{max} was up to 24°C. The ambient temperatures T_0, maximum smoke temperature T_{max}, the average smoke temperature T_{av} during the steady burning period, and the time t_{av} taken to reach T_{av} are extracted and shown in Table 1.

Values of t_5, t_{10}, t_{15}, t_{20}, t_{25} and t_{fa} are shown in Table 3 with h_n measured by visual inspection. The time t_{50} taken to fill 50% of the atrium with smoke (i.e. $h_n = 0.5$), and the time t_{80} taken to fill 80% of the space with smoke (i.e. $h_n = 0.2$) are also shown. Since the heat release rate curves for all the tests were roughly the same, the smoke layer descending time curves were similar with very little deviations. Further, it is observed that smoke had filled up the atrium before the fuel burnt out. Therefore, values of t_{fa} for all five sets of experiments were very close but shorter than t_B.

4. Comparison with smoke filling equations

An equation for h_n was developed earlier based on a simple two-layer zone model with the air entrainment rate calculated by a plume equation [22]:

Table 2
Smoke temperature rise in a typical test

Time/s	Smoke temperature rise/°C																			
	TA1	TA2	TA3	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14	TA15	TA16	TA17	TA18	TA19	TA20
0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	1.3	0.0
15	2.5	1.3	1.3	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	2.5	0.0	1.3	1.3	0.0	2.6
30	2.5	3.8	3.9	3.9	2.6	2.5	2.5	1.3	0.0	1.3	3.8	3.8	2.5	2.5	2.5	2.5	1.3	0.0	1.3	3.9
45	3.8	3.8	5.1	3.8	5.1	5.1	5.1	3.8	5.1	5.1	3.8	3.8	5.1	3.8	6.3	2.5	0.0	2.5	0.0	6.5
60	8.8	10.1	3.8	6.3	5.1	6.3	8.8	7.6	5.1	7.6	10.1	7.6	10.1	7.6	8.8	6.3	2.5	1.3	1.3	7.8
75	11.3	16.3	8.8	6.3	5.1	10.1	10.1	11.3	10.1	11.3	10.1	12.6	11.3	10.1	13.8	6.3	2.5	6.3	2.5	9.0
90	10.1	15.1	10.1	7.6	10.1	10.1	10.1	10.1	10.1	11.3	10.1	12.6	13.8	8.8	13.8	7.6	1.3	5.1	1.3	7.8
105	17.6	17.6	16.3	10.1	7.6	12.6	16.3	13.8	11.3	13.8	15.1	13.8	15.1	13.8	16.3	8.8	3.8	5.1	5.1	11.6
120	16.3	15.1	17.6	10.1	6.3	11.3	15.1	11.3	13.8	13.8	15.1	13.8	17.6	17.6	17.6	11.3	5.1	8.8	10.1	10.3
135	18.8	20.1	15.1	10.1	8.8	12.6	15.1	15.1	12.6	15.1	15.1	16.3	16.3	17.6	18.8	10.1	8.8	12.6	8.8	10.3
150	18.8	20.1	15.1	11.3	8.8	13.8	16.3	16.3	15.1	15.1	13.8	17.6	16.3	17.6	18.8	10.1	8.8	13.8	11.3	10.3
165	21.3	18.8	16.3	13.8	12.1	15.8	15.1	17.6	16.3	23.8	17.6	13.8	17.6	16.3	18.8	18.8	12.6	12.6	17.6	17.6
180	22.5	18.8	15.1	11.3	12.6	17.6	11.3	18.8	15.1	20.1	16.3	15.1	16.3	15.1	18.8	15.1	12.6	13.8	15.1	20.1
195	21.3	17.6	17.6	12.6	15.1	17.6	15.1	17.6	15.1	22.5	17.6	12.6	17.6	16.3	18.8	17.6	13.8	12.6	17.6	18.8
210	22.5	20.1	16.3	11.3	16.3	16.3	11.3	17.6	16.3	22.5	16.3	15.1	16.3	15.1	18.8	15.1	12.6	15.1	16.3	17.6
225	21.3	18.8	17.6	12.6	16.3	17.6	15.1	16.3	15.1	20.1	17.6	12.6	16.3	16.3	18.8	15.1	13.8	12.6	16.3	20.1
240	21.3	20.1	16.3	11.3	16.3	17.6	11.3	17.6	17.6	23.8	16.3	15.1	17.6	15.1	20.1	16.3	12.6	15.1	17.6	17.6
255	22.5	18.8	17.6	11.3	11.3	16.3	13.8	17.6	15.1	20.1	17.6	13.8	16.3	16.3	18.8	15.1	13.8	13.8	16.3	20.1
270	21.3	18.8	17.6	11.3	16.3	17.6	12.6	16.3	16.3	25.0	16.3	13.8	17.6	15.1	18.8	16.3	12.6	13.8	17.6	18.8
285	22.5	20.1	16.3	10.1	16.3	16.3	12.6	17.6	15.1	21.3	16.3	16.3	16.3	16.3	18.8	15.1	12.6	15.1	16.3	20.1
300	21.3	18.8	17.6	12.6	18.8	17.6	15.1	16.3	16.3	23.8	17.6	13.8	17.6	16.3	18.8	17.6	13.8	13.8	18.8	17.6
315	21.3	18.8	16.3	13.8	18.8	18.8	15.1	17.6	16.3	23.8	17.6	13.8	17.6	16.3	18.8	18.8	12.6	12.6	17.6	17.6
330	22.5	18.8	15.1	11.3	12.6	17.6	11.3	18.8	15.1	20.1	16.3	15.1	16.3	15.1	18.8	15.1	12.6	13.8	15.1	20.1
345	21.3	17.6	17.6	12.6	17.6	17.6	15.1	17.6	15.1	22.5	17.6	12.6	17.6	16.3	18.8	17.6	13.8	12.6	17.6	18.8
360	22.5	20.1	16.3	11.3	17.6	16.3	11.3	17.6	16.3	22.5	16.3	15.1	16.3	15.1	18.8	15.1	12.6	15.1	16.3	17.6
375	21.3	18.8	17.6	12.6	16.3	17.6	15.1	16.3	15.1	20.1	17.6	12.6	16.3	16.3	18.8	15.1	13.8	12.6	16.3	20.1
390	18.8	22.5	11.3	10.1	16.3	12.6	15.1	15.1	12.6	15.1	15.1	16.3	16.3	17.6	18.8	10.1	8.8	12.6	8.8	10.3
405	18.8	22.5	12.6	11.3	15.1	13.8	16.3	16.3	15.1	15.1	13.8	17.6	16.3	17.6	18.8	10.1	8.8	13.8	11.3	10.3
420	18.8	20.1	10.6	11.3	12.6	12.8	11.3	11.3	12.6	11.3	10.1	13.8	11.3	13.8	12.6	8.8	15.1	15.1	17.6	3.9
435	17.6	17.6	7.6	10.1	10.1	8.8	10.1	10.1	11.3	10.1	10.1	12.6	10.1	13.8	10.1	7.6	13.8	13.8	17.6	3.9
450	17.6	15.1	5.1	5.1	3.8	6.3	8.8	8.8	10.1	10.1	10.1	11.3	8.8	12.6	8.8	7.6	13.8	12.6	17.6	2.6

$$h_n = \begin{cases} \left[0.084\left(\dfrac{\alpha H^2 g}{\rho_0 c_p T_0 A^3}\right)^{1/3} t^{5/3} + 1\right]^{-3/2} & \text{for } t < t_s \\ \left[0.14\left(\dfrac{g Q_0 H^2}{\rho_0 c_p T_0 A^3}\right)^{1/3} (t - t_s) + \left(\dfrac{H}{h_s}\right)^{2/3}\right]^{-3/2} & \\ \text{for } t \geq t_s \end{cases} \quad (4)$$

where h_s is given by:

$$h_s = \left[0.084\left(\frac{\alpha g}{\rho_0 c_p T_0 A^3}\right)^{1/3}\left(\frac{Q_0}{\alpha}\right)^{5/6} + H^{-2/3}\right]^{-3/2} \quad (5)$$

Since the five tests gave similar results, average values of the parameter can be used for calculating h. Average values of the five tests were 1.66 MW for Q_0, 94 s for t_s and 0.1896 kW s^{-2} for α. Variations of h_n predicted by Eq. (4) using the averages of those measured parameters are plotted in Fig. 4. Experimental results of h_n deduced from the visual inspection method and the temperature method are shown.

In addition, methods for calculating h_n were proposed by Tanaka and Yamana [9] and Yamana and Tanaka [10]. For a t^2-fire without the steady burning part, h_n is given by:

$$h_n = \frac{1}{H\left(k_1 \dfrac{\alpha^{1/3}}{A} \dfrac{2}{5} t^{5/3} + \dfrac{1}{H^{2/3}}\right)^{3/2}} \quad (6)$$

Table 3
Smoke descending time

Test number	t_5/s	t_{10}/s	t_{15}/s	t_{20}/s	t_{25}/s	t_{fa}/s	t_{50}/s	t_{80}/s
1	75	90	100	125	190	235	95	145
2	65	80	95	125	175	210	90	140
3	80	90	105	130	185	240	100	145
4	85	100	110	135	200	270	115	150
5	70	95	110	135	190	215	115	150

where k_1 is a parameter appearing in the plume equation.

Results on h_n computed by the above equation using the measured parameters are also plotted in Fig. 4.

Another equation for calculating h_n with no smoke exhaust operating is recommended by NFPA-92B [16]:

- for t^2-fire:

$$h_n = 0.91 \left[\frac{t}{\left(\frac{1000}{\alpha}\right)^{1/5} H^{4/5} \left(\frac{A}{H^2}\right)^{3/5}} \right]^{-1.45} \quad (7a)$$

- for steady fire:

$$h_n = 1.11 - 0.28 \ \ln\left[\left(\frac{tQ_0^{1/3}}{H^{4/3}}\right)\left(\frac{A}{H^2}\right) \right] \quad (7b)$$

These equations hold for atria with geometries:

$$0.9 \leq A/H^2 \leq 14 \quad (8)$$

and

$$h_n \geq 0.2 \quad (9)$$

Eq. (7a) was used for $t < t_s$, and Eq. (7b) used for $t \geq t_s$ in putting in Fig. 4.

As shown previously, the smoke filling model given by Eq. (4) based on the point source plume expression is reasonably good to describe the smoke filling process for an atrium with the fire located at floor level. This is more suitable than the NFPA2 equation [16] given by (7a) or (7b) which holds only for either a t^2-fire or a steady burning fire. Further, the value of A^2/H of the PolyU/USTC Atrium is 0.37, lying outside the validity range given by Eq. (8). Results predicted from Tanaka's model [9,10] should be similar to those predicted by Eq. (4) except that the fire was taken as a t^2-fire.

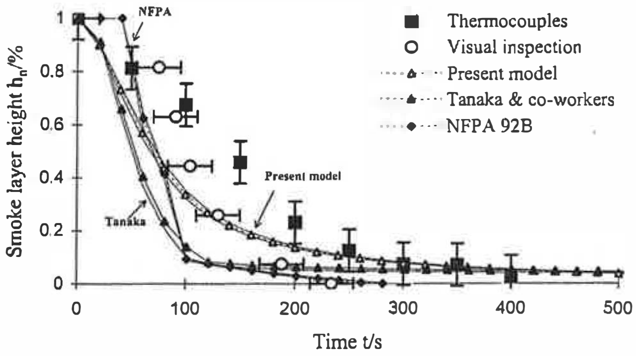

Fig. 4. Descending time of smoke layer.

5. Conclusion

Experimental studies on a natural smoke filling process at the new PolyU/USTC atrium were reported. Five hot smoke tests with liquid pool fires of size 2 × 2 m and heat release rate up to 1.6 MW were performed to study the smoke filling process, and to evaluate the smoke filling model.

Observation of the smoke layer interface height depended on the location of the interface positions. Since the density of the smoke layer increased while performing the tests due to mixing with cool air, it was very difficult to get the exact position of the interface following NFPA 92B [16] using smoke density distribution because of the huge space of the atrium. Practical experience of the research personnel is very important. Burning tests with similar conditions were repeated for getting better results. Optical smoke measuring instruments will be installed later for more accurate measurements.

Comparing the simple smoke filling model derived earlier given by Eq. (4) with the experiments, good agreement is observed. A smoke filling model based on the point source plume [22] equation is reasonably good to describe the smoke filling process.

Note that hot smoke tests [e.g. 18,19] are considered important in assessing the performance of smoke management systems. However, if the tests are carried out in the actual site, the fire cannot be so big as this would pose dangers to the research workers and damage the expensive decoration. Therefore, a full-scale burning facility is important for assessing different scenarios. This is particularly important as the possibility of implementing engineering performance-based fire codes is under review [17].

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