Review on Experimental Studies on Natural Smoke Filling in Large Spaces

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ABSTRACT Experimental studies on fire smoke filling in an atrium were carried out in a new full-scale burning facility: the USTC/PolyU Atrium. Three kind of pool size was designed: discs with diameter of 0.6m and 1.0m, square tray with side length of 2.0m. The pools were located at the floor with all the windows and vents of the atrium closed, leaving just a horizontal gap near the floor for supplying fresh air. Transient mass losses of the burning fuel, vertical temperature distributions and descending time of the smoke layer were measured. A simple model based on the zone model was compared with the tests and some smoke filling models appeared in the literature. **KEYWORDS:** large spaces, smoke filling, heat release rate, zone model.

INTRODUCTION

Large space buildings, such as multi-level shopping malls, theaters, luxurious hotels, indoor arenas and prestigious office buildings, are very popular in the whole world. The fire broke up in these buildings is a very important subject in fire field recent years. How to protect the occupants from the smoke hazards is a key facet on this subject. Because the space is large, and there are no barriers for preventing smoke spreading, it will be quickly for smoke spread to everywhere of this building or adjoining buildings. So determine the time for smoke descending to the hazardous level is essential. Many researchers have noticed this problem and did some works in theory analysis [1, 2, 3], but few full-scale experiments on large space fire were studied for the limit of facility[4, 5, 6] .

A full-scale burning facility, the USTC/PolyU Large Space Experimental Hall[7, 8], was constructed for experimentally studying atrium fires and evaluating the performance of the associated fire services systems in atrium buildings[9]. This is a joint project between the University of Science and Technology of China (USTC) and the Hong Kong Polytechnic University (PolyU). Outer dimensions of the atrium are 27.6 m(L)×18.1m(W)×30.6m(H), while the inner size is 22.4m(L)×11.9m(W)×27m(H).

The first stage of study in the USTC/PolyU Hall is on smoke filling process with a diesel pool fire placed at the floor level. Reviewing it becomes the objective of this paper. The pools were located at the center of the Hall. The sizes of pools are 0.6m and 1.0m(diameters) for discs and 2.0m(side length) for square tray. So fires with different powers were carried out. In these experiments, the all the windows and vents of the Hall were closed, only leaving a gap about 0.2m high on the door for air makeup. The heat release rates(HRR) ranged from several hundred kilowatt to several megawatt. A simple model for large space fire was validated with the experimental data and ASET model.

TWO-LAYER ZONE MODEL FOR THE SMOKE FILLING PROCESS

Two-layer zone model is used in the theoretical consideration of smoke filling process. Namely, the whole large space is divided into two zones, the upper hot smoke layer and the lower cool air layer. In each layer, the properties of the gas are considered identical. Based on these assumption and the mass entrainment rate formula of Heskestad[10] with some simplifications, the differential of smoke layer height with time can be expressed as follow: [11, 12, 13]

$$-\frac{\mathrm{d}Z}{\mathrm{d}t}=\frac{0.071Q^{1/3}Z^{5/3}}{A\rho_0} \qquad (1)$$

Heat release rate Q of a diesel pool fire can be modeled as an unsteady t^2-fire at the beginning stage, then as a constant fire with heat release rate Q_s at the steady burning stage.

$$Q=\begin{cases}\alpha t^2 & t<t_s\\ Q_s & t\geq t_s\end{cases} \qquad (2)$$

where α is the fire growth factor. For the diesel pool fire, it can be treated as ultra-fast fire, then α=0.1878. t_s is the time up to the steady stage deduced by:

$$t_s^2=Q_s/\alpha \qquad (3)$$

Substituting equation (2) into equation (1) and integrating it, the expressions for the smoke layer position as a function of time can be obtained:

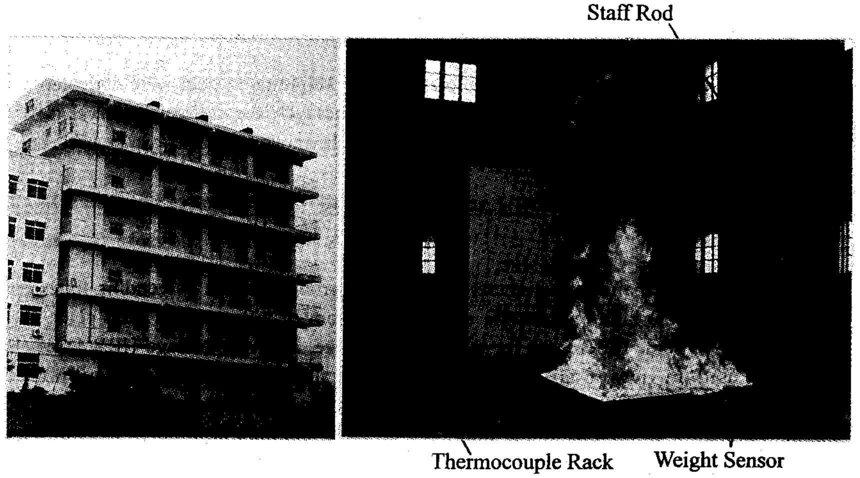
$$\left.\begin{aligned}\frac{Z}{H}&=[1+0.009\frac{\alpha^{1/3}H^{2/3}t^{5/3}}{A\rho_0}]^{-3/2} && (t\leq t_s)\\ \frac{Z}{Z_s}&=[1+0.042\frac{Q_s^{1/3}Z_s^{2/3}(t-t_s)}{A\rho_0}]^{-3/2} && (t>t_s)\end{aligned}\right\} \qquad (4)$$

where, Z_s is the smoke layer height at t_s.

THE EXPERIMENTS

The geometry of the USTC/PolyU Hall and the test arrangements are shown in figure 1. 15 times of diesel pool fire tests divided into 3 groups were performed in the past 2 years.

Group A: the pool size is a disc tray with diameter of 0.6m.
Group B is a disc tray with diameter of 1.0 m.
In Group C, the pool is a combined square tray with side length of 2m, which is consisted of 4 1m×1m trays.



(a) Outside view of the Hall (b) Test arrangement

FIGURE1. The USTC/PolyU Hall

All the fires were located on the center of the Hall floor. All ceiling vents and side windows of the Hall were closed, only leaving a gap on the door near the floor for supplying the fresh air.

In order to observe the smoke descending process, a staff rod was set on the east wall of the Hall (seen in figure1). Times at which the smoke layer descended to the following locations were recorded:

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}, on reaching the floor t_{fl}.

Smoke temperature was measured by the thermocouples. There are three thermocouple racks (type T, K and semi-conductor) in three corners. Each track includes 20 measuring points along the vertical direction with a interval of 1m. The top thermocouple is 1m down away the ceiling. For the smoke temperature was higher than the air, when the smoke reached the thermocouple, the temperature rise should be showed. Based on the temperature rise gained from the thermocouples, the smoke layer height can be deduced.

A pressure-sensitive platform set under the tray was used to measure the mass loss rate. During the fire, the pressure signals were sent to the computer by an collector and transformed to mass signal in the computer. Then the heat release rates of the fire can be gained through the formula $Q=\Delta \dot{m} h$. For the combined pool, only one tray's mass loss was measured, so the total heat release rates of fires were taken as 4 times of the values measured from the fuel tray weighted by the weighting system. The combustion heat of diesel, h was taken as 42,000 kJ/kg.

Large volume of data from the thermocouples and the weighting system were collected by the collector in the tests. The collector has 64 road passages, the colleting interval is 1.5 second. For the technic problem, in each test, only two thermocouple racks can be used.

RESULTS AND DISCUSSION

Tables 1-3 were the main fire parameters of the three groups and the descending times by eyes. Because of the high temperature affect, the bottom of tray was not keep plant, the steady HRR had some differences for the same pool size. Here the average HRR for each group was used. In view of tables 1-3, values of t_{fl} for all 5 tests in each group were very close, all shorter than t_B. Smoke filled up the Hall before the fuel burnt out. For group A, the smoke was hardly descending to the floor. For group B, the time descending to floor was about 6.5 minutes, so during such fires, the safety time for occupant to evacuate is about 6 minutes. For group C, this time decreased greatly, only about 4minutes. In this situation, it is very dangerous. The descending curves by observation from tables 1-3 were plotted in figure 2. From tables 1-3 and figure 2, it can also be seen that the smoke descending velocity slowed down with the time growth, because at the later of the fire, the plume entrained not only the air, but the smoke. This led the total volume of smoke decrease and the density of smoke thickened.

TABLE 1. Fire Parameters and Smoke descending times for Group A

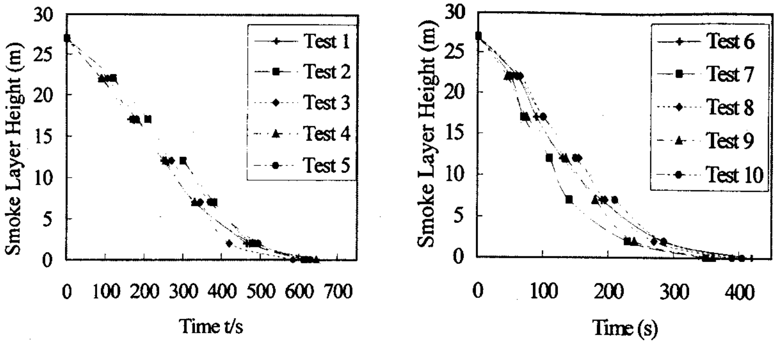
Tests	Mass of diesel m_f(kg)	Burning time t_B(s)	Ambient temp. T_0 (°C)	Q_s (kW)	t_5 (s)	t_{10} (s)	t_{15} (s)	t_{20} (s)	t_{25} (s)	t_{fa} (s)
1	3.7	720	20	215	135	200	300	360	450	600
2	2.9	720	20	203	120	225	300	360	480	585
3	3.1	840	19	228	105	180	255	330	450	--
4	3.0	690	21	247	105	165	240	345	480	--
5	3.1	900	20	248	90	165	250	330	465	--
Ave.	3.16	774		228	111	187	269	345	465	592

TABLE 2. Fire Parameters and Smoke descending times for Group B

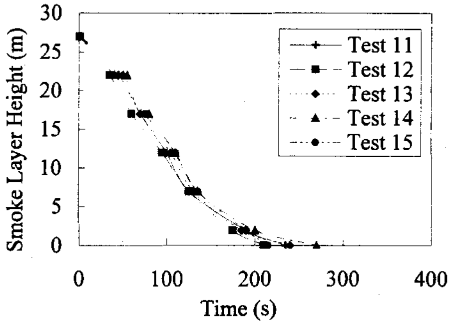
Tests	Mass of diesel m_f(kg)	Burning time t_B(s)	Ambient temp. T_0 (°C)	Q_s (kW)	t_5 (s)	t_{10} (s)	t_{15} (s)	t_{20} (s)	t_{25} (s)	t_{fa} (s)
6	4.5	480	17	393	45	75	120	195	300	420
7	5.1	510	16	420	60	105	130	195	270	315
8	5.3	585	10	383	55	96	150	190	280	396
9	4.8	516	15	391	50	75	105	175	290	390
10	4.8	530	10	380	60	90	130	190	285	420
Ave.	4.9	524		393	54	88	127	189	285	388

TABLE 3. Fire Parameters and Smoke descending times for Group C

Tests	Mass of diesel m_f(kg)	Burning time t_B(s)	Ambient temp T_0 (°C)	Q_s (kW)	t_5 (s)	t_{10} (s)	t_{15} (s)	t_{20} (s)	t_{25} (s)	t_{fa} (s)
11	5.7×4	780	23	1560	45	70	100	125	190	235
12	5.2×4	720	24	1600	35	60	95	125	175	210
13	5.5×4	600	24	1840	50	70	105	130	185	240
14	4.2×4	525	22	1680	55	80	110	135	200	270
15	5.8×4	810	22	1640	40	75	110	135	190	215
Ave.	21.12	687		1660	45	71	104	130	188	234



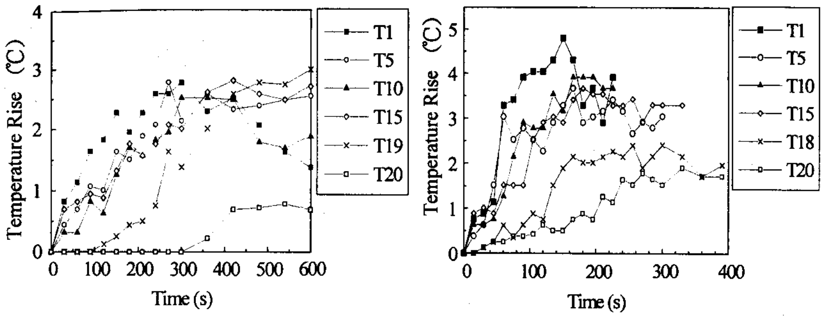
(a) Group A (b) Group B



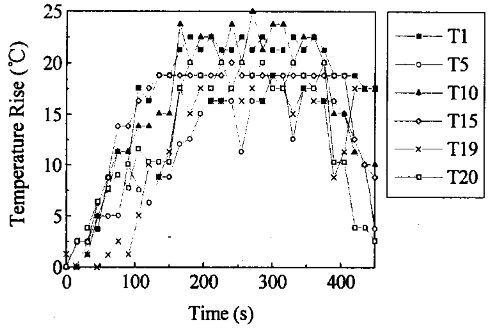
(c) Group C

FIGURE 2. Descending of smoke layer height by Observation

The average values of t_s for groups A, B and C are 35s, 46s, 94s, respectively. Typical Temperature rise curves of these three groups are plotted in figure 3. Ti means the temperature measured by the thermocoupl down away i m from the ceiling. It could be found that the highest temperature rises of hot smoke in groups A and B were only several degrees. It is very low. In group C, the temperature rise reached up to about 20℃, larger than results of A and B. However, it is much lower than the activation temperature for the temperature-sensitive detectors and alarms. So it is not suitable to install the temperature-sensitive sensors. From these figures, it also can be found that with the increasing of HRR, the lower thermocouples responded quicker. One side, it shows the smoke descending quicker. On the other hand, it indicates that the radiation affect to the lower thermocouples was more obvious. During the testes of group C, it was observed that the radiation from fire was very strong when the fire developed. The "radiation wave" from the fire could be insufferable just 5 m away. When the smoke descended to floor, the dark smoke was getting so heavy that the fire could be nearly invisible from the inspection room.



(a) Group A (b) Group B



(c) Group C

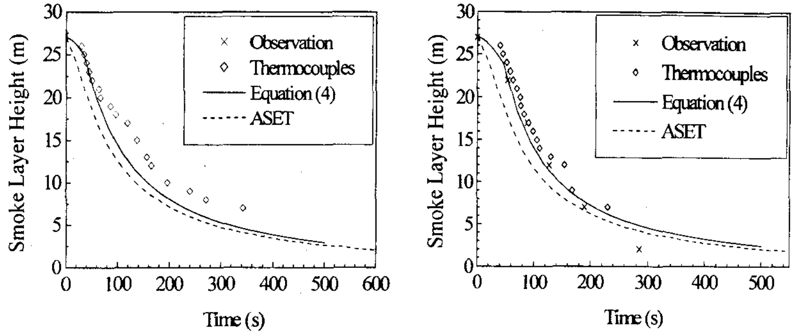
FIGURE 3. The typical temperature rise by thermocouples

When estimating the smoke layer height for larger fires through the temperature rise, the radiation affect should be considered.

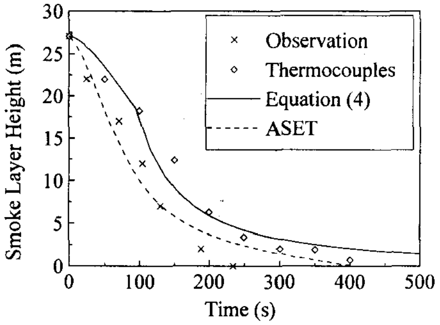
But with the time growth it is much greater than the tests. This is because at the latter stage the power of the fire had decreased, this made the temperature not rise obviously. But in the model of ASET, the fire power of latter stage was still taken as same as the steady stage.

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 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.

Variations of smoke layer height predicted by equation (4) with empirical temperature data measured over the three group tests were plotted in figure 4(a), (b) and (c). The results of Z deduced from the visual inspection method, the temperature method, the ASET model are plotted in figure 4 as well. Differences between the smoke layer interface heights measured by the temperature method and the smoke density distribution method are illustrated. The results of ASET are lower than the tests and equation (4). While the model of equation (4) is more close to the experiments. This illustrates that a smoke filling model based on point source plume equation is reasonably good to describe the smoke filling process. Compared among these three figures, it can be seen that with the fire is larger, the difference between the ASET and equation (4) is larger. During the tests, gasoline was used to ignite the diesel, the time growth to steady stage t_s were estimated more longer for large fire, this leads the descending calculated by equation (4) slower than the facts.



(a) Group A (b) Group B



(c) Group C

FIFURE 4. The development of smoke layer height

From the tests, we can also get that the smoke spreads very fast in a large space without barriers. For this 27-meter high Hall, the time for people to evacuate safely from top to outdoors from a pool fire of about 1.6MW was only about 4 minutes. This shows it is very urgent for the safety evacuation in the large space. The more evacuation measures should be taken in large space buildings.

CONCLUSIONS

Experimental studies on natural smoke filling process at the new USTC/PolyU Hall were reported. Fifth hot smoke tests with different pool size were performed to understand better the smoke filling process, and to evaluate the plume equation available for developing a smoke filling model for atria. The results of tests illustrate that the simple model based on the two-zone idea can predict the smoke movement in large space fire. In the tests, the least time for smoke descending down to the floor was less than 4 minutes, this indicates that the time for the occupant to evacuation is very little.

In a large space, the smoke temperature rise is very little, it is not suitable to install temperature-sensitive sensors in it.

Hot smoke tests 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, full-scale burning facility is important for assessing different scenarios.

At later stages, studies will be on:

- Smoke extraction system;
- Natural ventilation;
- Atrium sprinkler;

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REFERENCES

1. Tanaka, T. and Yamana, T., "Smoke control in large scale spaces - Part 1: Analytic theories for simple smoke control problems". Fire Science & Technology, 5:1, 31-40, 1985.

2. Klote, J. and Milke, J., Design of smoke management systems, ASHRAE Publication 90022, ASHRAE Atlanta, Georgia, U.S.A., 1992.

3. Mike, J.A., "Smoke management in covered malls and atria", in SFPE Handbook of Fire Protection of Engineering, 2nd edition, pp.4-247—4-258, National Fire Protection Association, Quincy, M.A.,1995.

4. Yamana, T. and Tanaka, T., "Smoke control in large scale spaces - Part 2: Smoke control experiments in a large scale space", Fire Science & Technology, 5:1, 41-54, 1985.

5. Hinkley, P.L., "Comparison of an established method of calculation of smoke filling of large scale spaces with recent experiments", Fire Science & Technology, 8:1, 1-8, 1988.

6. Huo, R., Fan, W.C., Yuan, L.M., Li, Y.Z., Jin, X.H., Chow, W.K., Cui, E., Fong, N.K., Ho, P.L., "Studies of smoke filling process in an atrium", Proceedings of '98 Shanghai International Symposium on Fire Protection of High-rise Building, Shanghai, China, 1998.

7. Huo, R., Fan, W.C., Yuan, L.M., Deng, H., Chow, W.K., Fong, N.K., Ho, P.L., "The construction of a large space fire experimental hall and some preliminary tests", Fire Safety Science in Chinese, 7:1, 8-13, 1998.

8. Chow, W.K., Fong, N.K., Cui, E., Ho, P.L., Wong, L.T., Huo, R., Fan, W.C., Li, Y.Z., Yuan. L.M., "PolyU/USTC Atrium: A Full-Scale Burning Facility-Preliminary Experiments", J. of Applied Fire Science, 8:3, 229-241, 1998-99.

9. "Guide for smoke management systems in malls, atria and large area," NFPA 92B, National Fire Protection Association, Quincy, M.A., U.S.A., 1995.

10. Heskestad, G., "Engineering Relations for Fire Plume", Fire Safety Journal, 7:1, 25-32, 1984.

11. Li, Y. Z., Huo, R., Zhou, J.J., Jin, X.H., Cui, E., Chow, W.K., "A study on the smoke movement in atrium fire", Fire Science and Technology, Tianjin, China, No.3 pp.4-8(1999).

12. Li, Y. Z., Huo, R. Yuan, L.M., Li, P.D., Fan, W.C., Cui, E., Chow, W.K., "Study of Smoke Filling Process in an Atrium", J. of University of Science and Technology of China, 29:5, 590-594, 1999.

13. Li, Y. Z., Huo, R., Cui, E., Chow, W.K., "Experimental studies on smoke filling in atria with large fire", Proceedings of '99 international Symposium on City Fire Safety. Huangshan, Anhui, China, 1999.