Comparison of Rise Time of Free Smoke Plume Front Predicted by a Field Model with Full-Scale Experiments

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Abstract

A fire field model Fire Dynamics Simulator (FDS) version 3.10 will be used to predict the rise time of free buoyant plume front in this paper. Numerical simulations were on configurations same as a set of full-scale burning tests carried out recently in a big atrium. Track of the plume front was deduced from 'sudden temperature rise' on the numerical thermocouples. Results show that the rise time of these plume fronts predicted by FDS version 3.10 are slightly shorter than the experimental data.

Keywords: rise time, buoyant plume front, Fire Dynamics Simulator (FDS), full-scale tests

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1. Introduction

There are many spaces with tall ceilings for buildings in the ‘city groups’ of the Far East. Examples are large atriums, tall light wells and internal building voids. There are potential fire hazard in those tall buildings, giving new challenges for designing fire protection systems. Many studies were reported on the smoke filling process [eg.1, 2], but not on other key issues. For example, it will take long travelling time for the ‘smoke’ front to reach the ceiling for a fire in those spaces with tall ceilings.

However, zone type models seem to can not account for this rise time [3], but it is considerable when evaluating the Available Safety Egress Time according to critical smoke layer interface height, because firstly a smoke layer has not formed before the plume front reach the ceiling. And this rise time should also be understood while designing smoke management systems, such as the critical opening time for the natural smoke vents installed at the ceilings.

The temperature, velocity profiles, turbulent flow structures, combustion characteristics, and other dynamic characteristics under different fire scenarios were studied numerically and experimentally in the literature [4-10]. Dynamics of buoyant plume are useful, but rise times of the buoyant plume front should be further studied.

With the rapid development of Computational Fluid Dynamics (CFD) due to the fast development of fire dynamics, fire field models can be simulated more successfully. The software package, Fire Dynamics Simulator (FDS), based on Large Eddy Simulation (LES) with a postprocessing visualization tool, SMOKEVIEW, had been developed by National Institute of Standards and Technology (NIST) USA for simulating fires [11]. This model was applied to study different fire scenarios including dynamics of fire plume [12]. Some comparisons and verifications were also performed for this model with full-scale test data on fire dynamics [13] and other prediction methods on smoke layer interface height [14].

Since zone type models can not solve this rise time, it seems that an available way is to resort to field models. Before these field models applied to predict this rise time, experimental verifications should be performed to see how well results will be achieved. However, it seems that there are very few studies touched upon this, especially full-scale verification studies. In this paper, the rise times of free buoyant plume fronts will be studied by FDS version 3.10. Results are compared with full-scale burning tests carried out at the PolyU/USTC Atrium. The way to track the plume or smoke front, the dependency of rise time of plume front on grid size in z-directions for FDS predictions are also discussed.

2．Full-scale Experimental Studies

A series of full-scale burning tests had been carried out for measuring the travelling time of plume front induced by a fire at the PolyU/USTC Atrium as reported earlier on demonstrating some experimental correlations [15]. Experimental arrangement in the hall is shown in Fig. 1. Two key quantities were measured in each test:

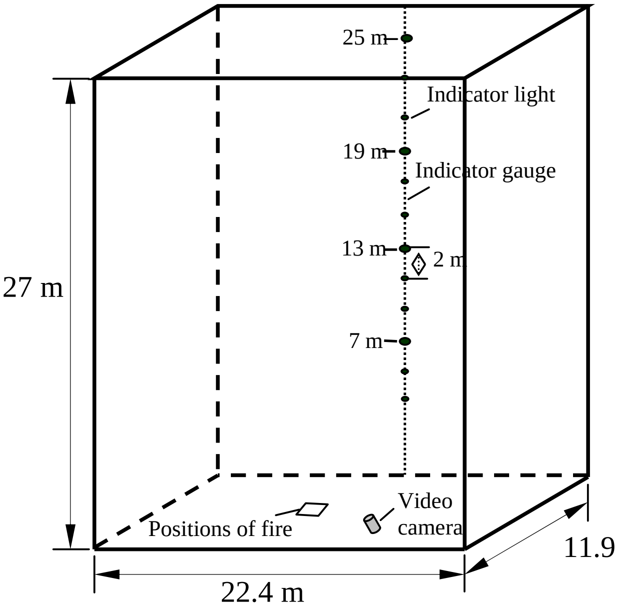


Fig. 1 PolyU/USTC Atrium

- The time taken for the plume front to reach 7 m, 13 m, 19 m, 25 m and the ceiling from the floor level;
- The transient mass of the burning fuel.

Indicator lights were arranged along a vertical string installed at the eastern side-wall of the atrium. Lights with two colours, red and yellow, were used. The red lights were placed at 2 m intervals, with the lowest one 3 m above the floor. The yellow lights were only placed at four heights, 7 m, 13 m, 19 m and 25 m above the floor. The times taken for the buoyant plume front to reach these four heights immediately after igniting the pool fires were recorded by an observer at the floor level. Another observer stayed at a higher position to record the time taken for the smoke front to reach the ceiling. A video camera was placed at the floor level for recording the whole rising process.

Diesel was put into square trays at the centre of the Atrium as shown in Fig. 1. A weighting system with six sensors was developed for measuring transient mass of the fuel in one of the trays.

3. Numerical Simulations

CFD simulations were carried out by Fire Dynamics Simulator (FDS) version 3.10.

Same square pools as full-scale tests were used as fire sources for CFD simulations. As the heat release is a key factor to determine the rise time of buoyant plume front, transient heat release rates input to the software were specified by following the corresponding experimental results. The temperatures at 7 m, 13 m, 19 m, 25 m and 27 m at the axis above the fire source was recorded by numerical thermocouples for each simulation. The time taken for the smoke front reaching these five heights will be indicated by the sudden temperature rise recorded at these heights.

The same non-uniform gird systems were used in the plume region for all the free plumes. The total domain were divided into 72 × 36 × 162 parts along the x-, y- and z-directions. Finer grids were specified along the x- and y- direction near the plumes. The overall and zoomed views of the grids are shown in Fig. 2.

The computing platform for the simulation is a personal computer with 2.4 GHz and 1 GB RAM. All cases were run for 60 s of simulation.

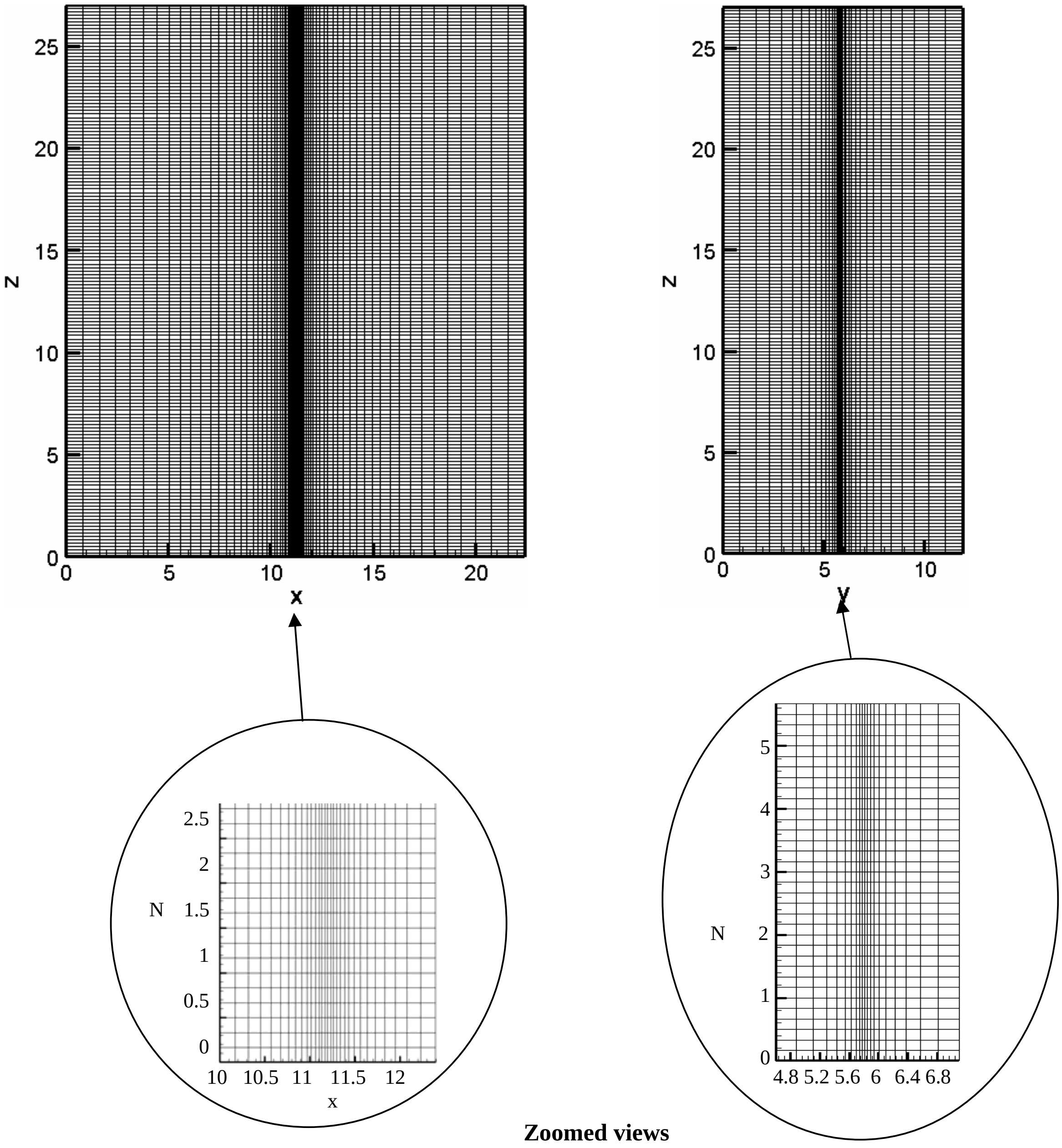
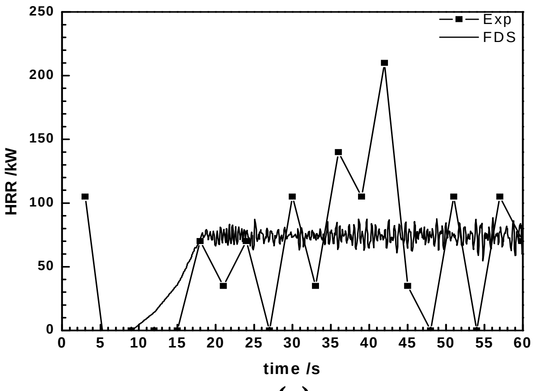


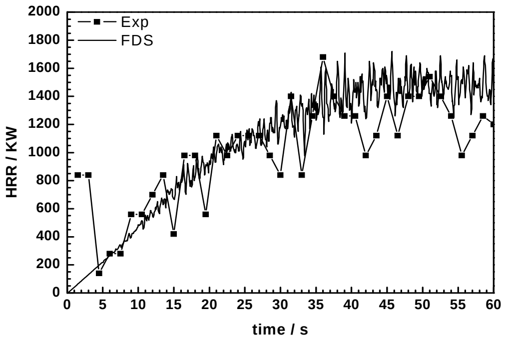
Fig. 2 Grids for numerical simulation by FDS

4. Results and Discussion

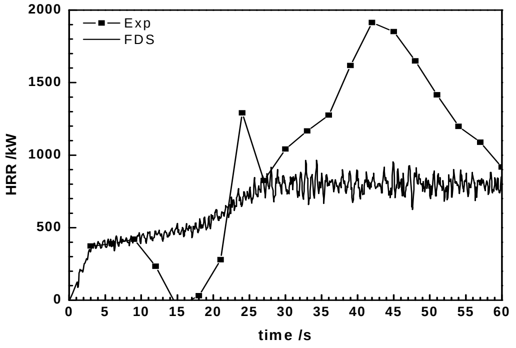
Keeping the same heat release rates between full-scale burning tests and FDS simulator is a key and fundamental point for comparing the rise times of plume fronts. This point must be investigated first. The heat release rates of the fires in the full-scale burning tests were estimated from the measured transient mass loss rate of the fuel. The heat of combustion of diesel was taken to be 42,000 kJkg^{-1}. The heat release rates of fires for full-scale tests and numerical predictions are shown in Fig. 3. It is observed that the development of fire source in numerical studies is nearly the same as that in full-scale tests except test1 and test3, in which the heat release rate measured in full-scale tests oscillated some large. Typical temperature contours and velocity vectors at 10s after ignition predicted by FDS are also incidentally shown in Fig. 4



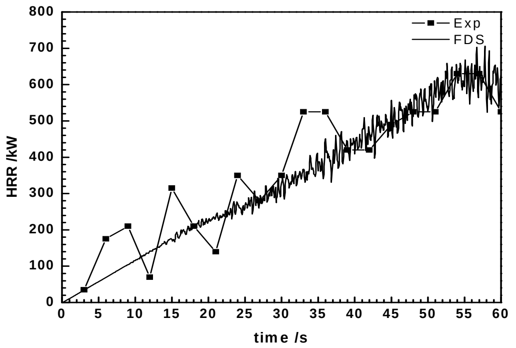
(a)



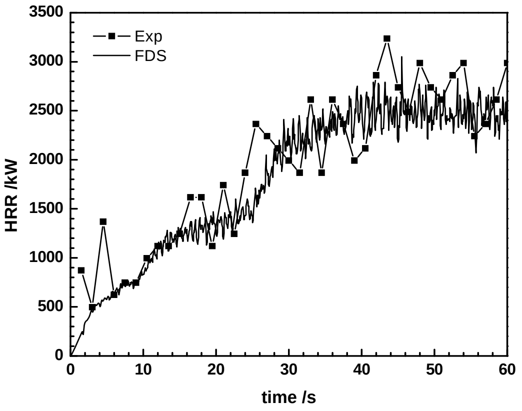
(b) Test 2



(c) Test

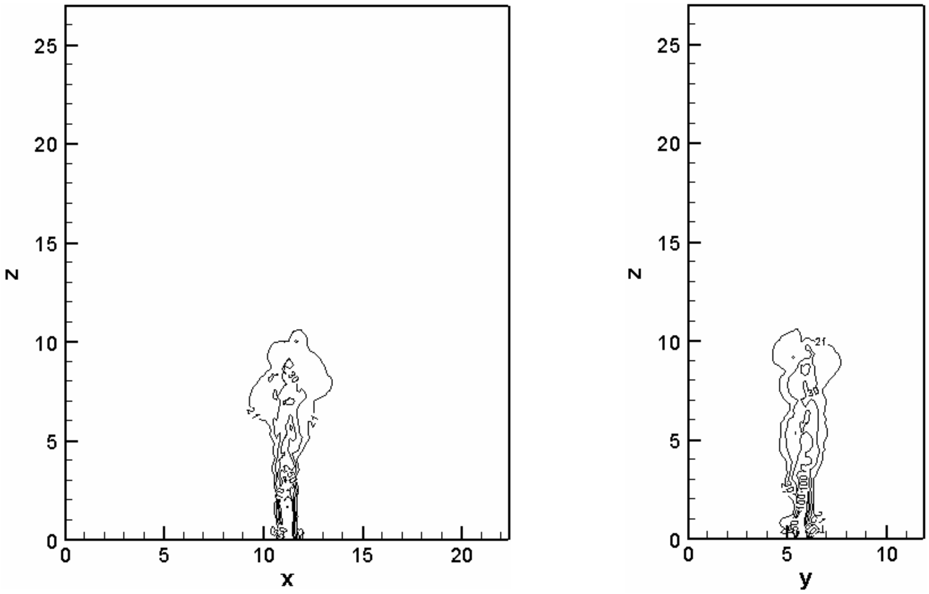


(d) Test 4

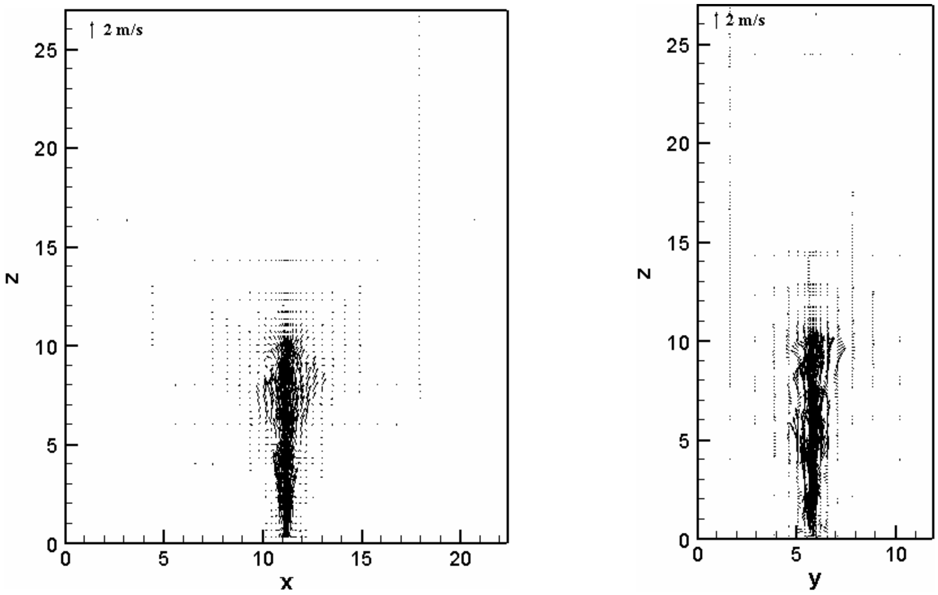


(e) Test 5

Fig. 3 Heat Release Rates by FDS and full-scale tests



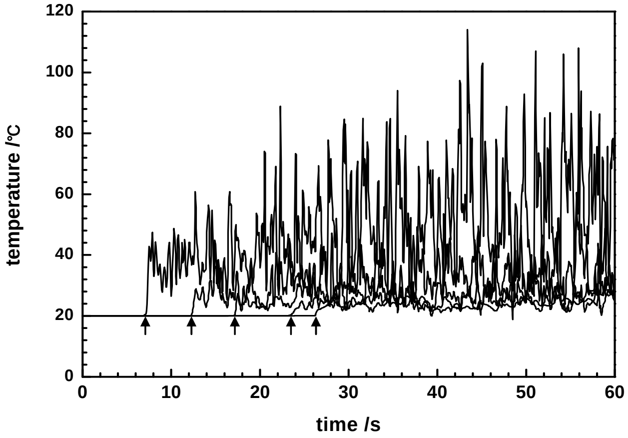
(a) Temperature contours



(b) Velocity vectors

Fig. 4 Temperature contours and velocity vectors in plume field predicted by FDS

Before comparison about the rise time of plume front taken between the FDS predictions and full-scale tests, the way used in FDS to track the plume and smoke fronts should be carefully studied. A thermal couple based way was ever used by former researchers to track the corridor ceiling jet front [16] and smoke layer interface front [1, 2] in fire experiments. This method had also been used and verified by others in the literature [16, 17]. So, the smoke plume front here was indicated by the sudden increase in temperature measured by thermocouples at different heights. Typical temperatures predicted at the five heights above the fire are also shown in Fig. 5.



(***Arrows:*** *Arrival of smoke front determined by sudden temperature rise.*)

Fig. 5 Predicted temperature at the five heights by FDS

In using the ‘sudden temperature rise’ recorded by FDS, the rise times for fire plume fronts to reach the five heights were estimated. Those predicted results on the rise time are compared with the full-scale tests in Table 1. The rise times for plume fronts predicted by FDS and that observed in full-scale tests are also plotted against the distance above the fire source in Fig. 6. It is observed that the rise times of buoyant plume fronts predicted by FDS were near to, although mostly somewhat earlier than, that observed in full-scale tests. Especially for tests except test1 and test3 in which heat release measured in full-scale tests were not so good, the rise times of buoyant plume fronts predicted by FDS were just slightly earlier than that observed in full-scale tests. So, it seems that FDS will give somewhat conservative predictions for the rise time of buoyant plume front to a certain height above fire source.

Table 1. Summary of results predicted are measured

		Time taken for plume front to travel / s														
Test		**1**			**2**			**3**			**4**			**5**		
Pool size		0.35 × 0.35 m			Two pool trays of size 0.7 × 0.7m			0.8 × 0.8 m			0.9 × 0.9 m			four pool trays of size 0.7 m × 0.7 m		
		Predict		exp	Predict		exp	Predict		exp	Predict		exp	Predict		exp
		0.5[1]	1[2]		0.5	1		0.5	1		0.5	4.2	4.2	6.3	1	
Height / m	**7**	14.6	14.7	8.5	5.78	5.78	4.36	7.08	7.21	8.7	7.08	7.08	10.0	4.45	4.45	5.0
	13	18.9	18.9	12.1	9.13	9.18	7.39	12.3	12.4	11.9	11.3	11.3	14.0	6.67	6.72	7.6
	19	28.6	28..6	18.1	15.2	15.2	11.29	17.2	17.2	15.2	16.2	16.2	20.6	9.9	9.97	11.3
	25	35.5	35.5	27.6	21.3	21.3	16.11	23.6	23.6	19.7	17.3	17.3	28.8	14.5	14.7	15.2
	27 (ceiling)	38.5	38.6	45.1	22.0	22.1	23.79	26.3	26.4	28	17.3	17.3	28.8	16.1	16.3	18.9

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[1] Determined by temperature rise of 0.5℃

[2] Determined by temperature rise of 1℃, used in Fig.6

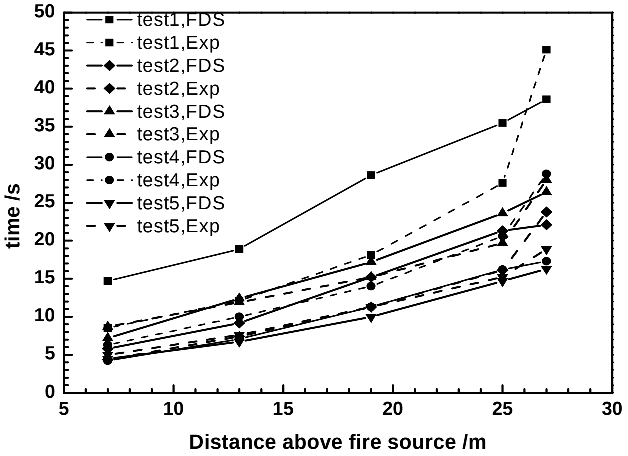
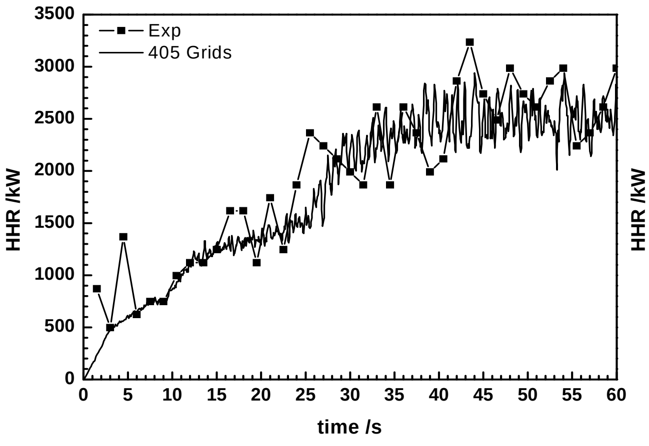


Fig. 6 Comparison of rise of plume fronts by FDS and full-scale tests

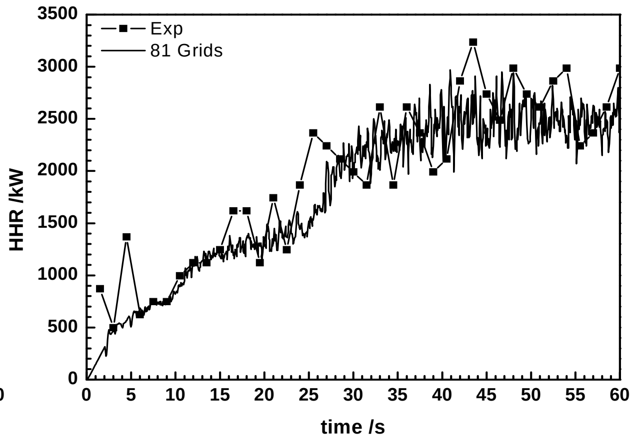
Sensitivity analysis on the gird sizes along the vertical z-direction was carried out with very fine grids in the x- and y-directions for the plume region. A simulation was also conducted with 405 grids, 81 grids and 45 grids in the z-direction for test 4. Simulation results are summarized in table. 2. Comparisons of HRR and rise times of plume front are shown in Figs. 7 and 8. In view of Fig. 7 and Fig. 3(d), the results on the HRR were almost the same, but merged more with experiments for more grids in the z-direction. As also shown in Fig. 8, the results on the rise times of buoyant fire plume front to reach the five heights for 405 grids and 162 grids are very close and being more nearer to that observed in full-scale tests than the other two cases in which less grids were specified.

Table.2 Simulation result of z-direction grid-dependent cases

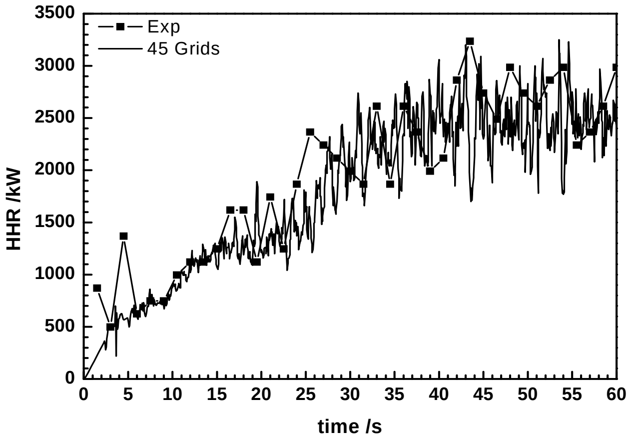
Number of grids in z-direction		405	162	81	45	Experimental rise time /s
Grid size in z-direction (cm)		6.67	16.67	33.33	60	
Rise time /s	7	4.08	4.45	4.51	3.97	5
	13	6.96	6.72	6.6	5.58	7.6
	19	10.5	9.97	9.66	9.85	11.3
	25	14.5	14.7	12.5	12.2	15.2
	27	16.3	16.3	14.2	13.6	18.9



(a) 405 grids in z-direction



(b) 81 grids in z-direction



(c) 45 grids in z-direction

Fig. 7 Heat Release Rate of test 4 with different grid numbers in z-direction

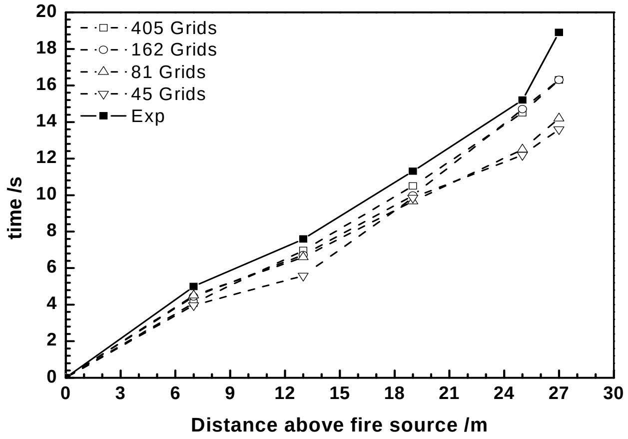


Fig. 8 Rise time of plume front of test4 with different grid numbers in z-direction

Care should be taken in assigning the computing mesh system while using FDS to predict the rise time of buoyant fire plume front. Under the condition of fine enough grids were specified for the near plume region in the x- and y- direction to capture the fire, at least 16.67 cm small size grids should also be needed in the z-direction.

5. Conclusions

The rise times of free buoyant plume fronts induced by pool fires in a tall atrium were predicted by FDS. Results are compared with full-scale burning tests at the PolyU/USTC Atrium. Smoke front of the buoyant plume can be predicted fairly accurately by the 'sudden temperature rise' method. The predicted rise time is slightly earlier than that measured from experiments. More conservative predictions for the buoyant plume front to reach ceiling will be achieved from FDS version 3.10. Care should be taken to specify fine enough grid size along the z-direction. For example, the grid size along z-direction shall be less than about 17 cm.

In some real-scale tests, there were oscillation of heat release rate in burning large pool fires. This point should be considered in studying effect of fire size to rise time of plume front. Future work would be performed with a more stable fire to get steady burning after ignition. Using fuel of premixed gases or liquids with lower boiling points might be better.

Acknowledgement

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