Analysis of Impact of Natural Supply on Smoke Exhaust in a Ship Cabin by Comparison of a Full-scale Experiment and Fire Simulations

Wang W.[1], **Peng C.**[1,] *, **Guo Y.**[1], **Peng H.**[2], **Zhu D.**[2], **Lu J.**[2]

[1] *School of Physical Sciences, University of Science and Technology of China,*
Hefei, Anhui, China
[2] *Science and Technology on Reactor System Design Technology Laboratory,*
Nuclear Power Institute of China, Chengdu, Sichuan, China
**Corresponding author's email: pengch@ustc.edu.cn*

ABSTRACT

Ship cabin fire accidents, on the one hand, might badly affect the integrity of ships and the safety of people, on the other hand, possibly result in the loss of safety-related equipment functions. Therefore, it is sensible to evaluate fire risk in ship cabins. Based on full-scale experimental tests, fire simulations by CFAST and FDS were conducted in this study to evaluate the effect of the size of the supply opening on smoke exhausts, and the size was changed by adjusting the upper height of the supply opening in the full-scale experimental tests and fire simulations. According to the experimental configurations, six groups of tests in this study were conducted by changing the upper heights as 0.1, 0.3, 0.5, 0.7, 0.9, and 1.1 m, and smoke layer temperatures, and smoke layer heights from experimental tests and fire simulations were selected as several indicators for the evaluation. By comparing full-scale experimental tests with fire simulations, it was shown that different sizes of natural supply vents have different effects on the effectiveness of smoke exhausts. More specifically, having a supply opening, compared with no supply opening, can effectively reduce smoke layer temperatures and increase smoke layer heights, which has been proven by full-scale experimental tests and fire simulations in this study.

KEYWORDS: Ship cabin fire, smoke exhaust, CFAST, FDS.

INTRODUCTION

Ship fire accidents, despite the fact that they account for 10% of total ship accidents, may lead to severe consequences, since they can destroy main ship functions and lead to total loss of the ship. Therefore, all safety regulations require prevention and mitigation of fire accidents in ship cabins [1].

A large amount of toxic, high-temperature smoke gases is produced in ship cabin fire scenarios, which not only poses a threat to sailors' safety, but also makes it difficult to suppress the fire. Moreover, ship cabins are generally narrow and lack independent mechanical ventilation. Once fire accidents occur there, if not tackled appropriately, not only will people's lives and facilities' design functions be threatened, but also the integrity and safety of the ship might be challenged to some extent. Ventilation systems are normally integrated and designed as part of ship cabins for smoke exhaust. Apart from that, mobile exhausting smoke equipment is used for smoke exhaust as well. For ship cabins where doors are the only natural supply vents, smoke exhaust by negative pressure, produced by mobile fans and ducts, is the only choice. Therefore, it is sensible and reasonable to evaluate how the natural supply vent's size affects smoke exhaust in ship cabins with a single door.

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CFAST is a two-zone fire model capable of predicting the fire-induced environmental conditions as a function of time for single-compartment or multi-compartment fire scenarios. It subdivides each fire compartment into two zones, in order to numerically solve differential equations, and the two volumes are assumed to be homogeneous within each zone. By using the ideal gas law and solving the equation of heat conduction into the walls, to the model simulates the environmental conditions generated by the fire [2].

FDS is a computational fluid dynamics (CFD) fire model of fire-driven fluid flow. The model numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow with an emphasis of mass, momentum, and energy. These equations are approximated as finite differences and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate smoke movement and sprinkler sprays [3].

Chen et al. evaluated the influence of air volume rate of mechanical vents on smoke exhausts in atrium buildings by using FDS [4]. Li et al. conducted experiments to explore the influence of different air-supplement conditions on mechanical smoke exhausts [5]. Ji et al. evaluated the influence of the relative location of the smoke exhaust opening to fire source on mechanical smoke exhaust efficiency in a long channel by conducting experiments in a bench-scale long channel [6]. Yuan and Zhang analyzed smoke transport and mechanical smoke exhaust in buildings by the Large Eddy Simulation method [7]. Wang et al. developed a field-zone coupling model of fire smoke propagation for ship cabin fires [8]. Zou et al. simulated experimental fires with a CFD package based on a modified set of Navier-Stokes equations for thermally driven buoyant flow and Large Eddy Simulation while also using a two-zone zone model to explore the descent law and temperature distribution of the smoke in cabin fires [9]. Hu et al. conducted a series of heptane pool fire experiments under different diameters of oil pans in an enclosed cabin [10]. Li et al. developed a model for predicting smoke filling time in a compartment with ceiling vents and compared it with a series of experiments [11]. You et al. carried out full-scale burning tests to explore the effect of smoke controlling with mechanical smoke exhaust under cabin fires and to evaluate the application ranges of three classical fire plume correlations including Heskestad model [12]. Zhang et al. simulated the aircraft cabin enclosed fire with PyroSim from FDS and evaluated the cabin smoke spread speed, visibility and temperature changes over time under two typical scenarios of cabin doors closed and cabin doors open [13]. You et al. carried out full-scale burning tests to study cabin fires under sprinkler and mechanical smoke exhaust and results show some critical combinations of pressure and fan extraction rate for controlling or extinguishing the fire. They also did a series of full-scale investigative burning experiments by a special model to test and determine the precise efficiencies of mechanical smoke discharge at lower levels in case of cabin fires [14-15]. Li et al. developed a fire model with analysis of smoke layer heights, self-extinction time, the cabin temperature at the quenching time and CO density based on the study of the fire behavior and the smoke characteristics in an enclosed ship cabin [16]. Salem et al. used a zone fire model, BRANZFIRE, to assess the effect of changing the size of the compartments on the time available for occupants to escape safely from a fire onboard [17].

Most previous studies focused on smoke exhaust evaluations in civil buildings, while the smoke analysis in ship cabin fires mostly emphasizes the characteristics of smoke flow in ship cabins with an opening on the ceiling, rarely involved in one-door ship cabin fires. In order to analyze the impact of a natural supply vent size on smoke exhaust in a ship cabin with a single door, a full-scale experiment from another paper is referenced, while fire simulations by using CFAST and FDS are conducted in this study. The natural supply vent size is changed by adjusting the upper height of the supply opening, and smoke layer temperatures and smoke layer heights from experimental tests and fire simulations are used as parameters for effect evaluation and comparison between fire simulations and experiments.

METHODOLOGY

Full-scale experimental tests

Full-scale experimental tests were conducted in a model ship cabin with a single opening by Ren et al. [18]. As shown in the Fig. 1, the experimental cabin is 5 m wide, 3 m deep and 2.5 m high. The ignition source is diesel oil in a square pool, located in the center of the experimental cabin on the floor. The lower edge of the natural supply is 0.1 m above the floor and the natural supply size is changed by the upper height of the natural supply opening, which could be achieved by using a mobile smoke proof curtain. A compressible air duct, made of composite heat-resistant materials, and a mobile fan whose rated air flow is 0.635 m^3/s, were used in the experimental tests. Thermocouples are installed every 1.0 m apart at the height of 1.6 and 2.5 m, and another five thermocouples, at the height of 0.2, 0.55, 0.9, 1.25 and 1.6 m above the floor, are installed at the natural supply opening as shown in the Fig. 1. Temperatures are measured with K-type sheathed thermocouples.

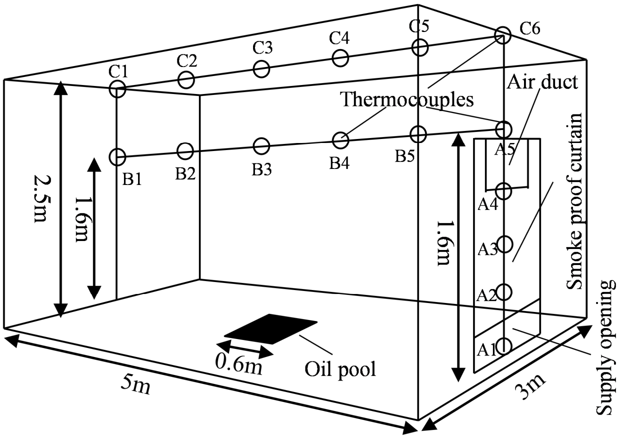


Fig. 1. Geometry of the experimental cabin [18].

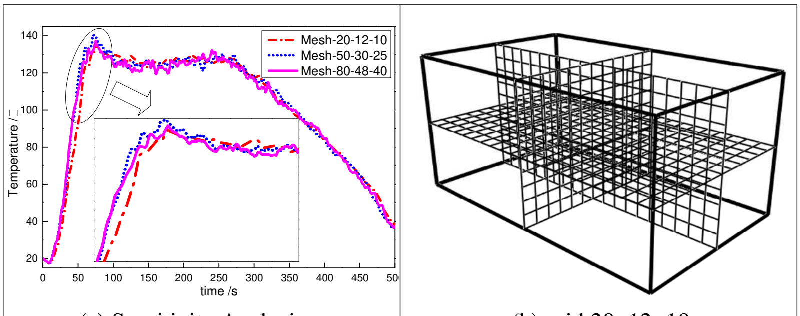
Six working conditions 1-6 in this study were set by adjusting the upper heights of the supply vents as 0.1, 0.3, 0.5, 0.7, 0.9 and 1.1 m, with areas of the supply vents corresponding to 0, 0.16, 0.32, 0.48, 0.64 and 0.80 m^2, as shown in Table 1. In order to test the effect of the natural supply on smoke exhausts, it was assumed that the mobile fan was activated at 60 seconds after fire ignition.

Table 1. Experimental configurations for tests 1-6

Test	Upper height of supply opening /m	Area of supply opening /m^2
1	0.3	0.16
2	0.5	0.32
3	0.7	0.48
4	0.9	0.64
5	1.1	0.80
6	0.1	0.00

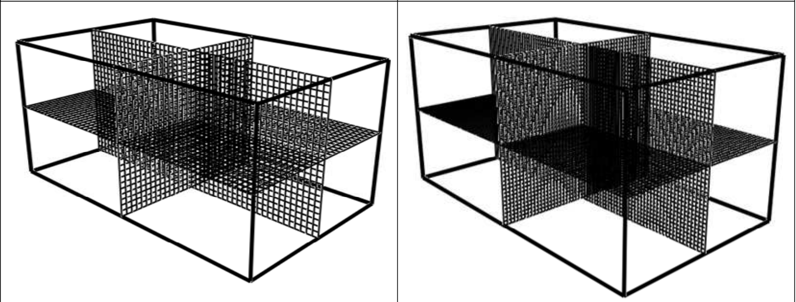
FIRE SIMULATIONS

Unlike CFAST, which is a two-zone model, it is necessary to evaluate mesh sensitivity when FDS is used for fire modeling. Figure 2(a) shows temperature changes measured by the thermocouple (labeled as B1) at the height of 1.6 m opposite to the wall with the door on it, in different grid numbers as shown in Fig. 2(b)-Fig. 2(d). In this study, the model with 50×30×25 grids was used for fire modeling.



(a) Sensitivity Analysis

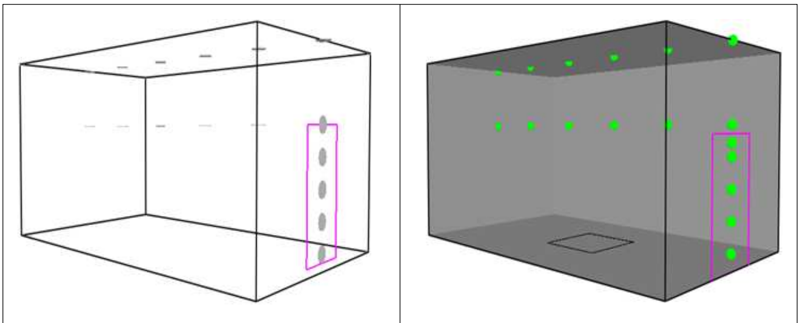
(b) grid:20×12×10



(c) grid:50×30×25

(d) grid:80×48×40

Fig. 2. Mesh Sensitivity Analysis of FDS.



(a) Fire Model by CFAST

(b) Fire Model by FDS

Fig. 3. Fire model for CFAST and FDS.

Figure 3(a) shows the fire model by CFAST. As shown in Fig. 3(a), targets were installed every 1.0 m apart at the height of 1.6 and 2.5 m, in order to record smoke layer temperatures surrounding these targets. Smoke layer heights can be automatically calculated. The fire source is located in the center of the room on the floor. Figure 3(b) shows the fire model by FDS, which is a fluid dynamics model. As seen in Fig. 3(b), thermocouples were installed every 1.0 m apart at the height of 1.6 and

2.5 m, in order to record smoke layer temperatures. Smoke layer heights can be automatically calculated by FDS, as long as we set relevant commands in the input file, since FDS can give an estimate of smoke layer heights at different locations according to the temperature stratification phenomenon. Technical details can be found in the FDS User Manual.

According to conditions in experimental tests 1-6, essential parameters for fire modeling by CFAST and FDS were evaluated. In this study, all these parameters were used for modeling processes, and Yi et al. provided technical details for most of these parameters as shown in Table 2 [19].

Table 2. Input parameters for fire modeling by CFAST and FDS

Parameters	Value
Shape of diesel oil pool	Square
Area of diesel oil pool	0.36 m^2
Depth of diesel oil pool	0.2 m
Density of diesel oil	810 kg/m^3
Heat of combustion	40000 kJ/kg
Mass loss rate	0.0065 kg/s
Time to peak release rate	30 s
Peak heat release rate	156.0 kJ/s
Steady burning period	220 s
Decay time	250 s
Combustion efficiency	0.60
Rated air flow of mobile fan	0.635 m^3/s
Radiant fraction	0.35

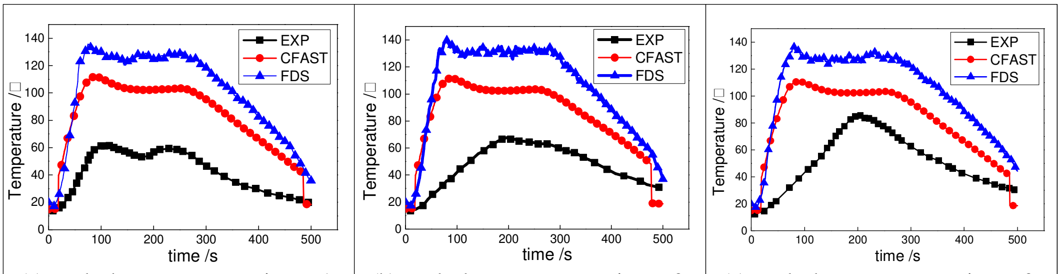
RESULTS AND DISCUSSION

Smoke layer temperature analysis

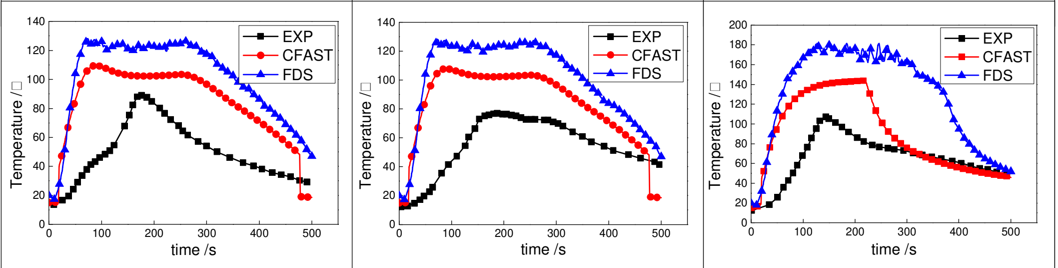
It is assumed that the average height from the ground eye level is 1.6 m, so smoke layer temperature at the height of 1.6 m was taken as one of the damage criteria in this study. In order to avoid temperature fluctuations caused by mixing of natural air and smoke, the thermocouple labeled as B1, at the height of 1.6 m and located opposite to the wall with the door on it, was selected to record temperatures for both experimental tests and fire simulations.

The smoke layer temperatures for experimental tests and fire simulations by CFAST and FDS during six working conditions are shown in Fig. 4. As shown in the figure, temperatures rise quickly after fire ignition, reach a peak, subsequently decline with time, and no obvious fluctuations in temperatures are observed when the mobile fan is activated at 60 seconds after ignition. Obvious differences in temperatures between experiments and fire simulations are shown in Fig. 4, even though the same trend is observed during the whole time.

Average and highest smoke layer temperatures for six experiments (tests 1-6) are shown in Table 3. In terms of average smoke layer temperatures, test 1 is the most effective and test 5 is the least effective for smoke exhaust, while with regard to highest temperatures, test 1 is the most effective and test 4 is the least effective. However, a different trend is seen from the perspective of the fire simulation results. In terms of average smoke layer temperature, test 1 is the most effective and test 2 is the least effective for smoke exhaust for both FDS and CFAST, while test 5 is the most effective for both FDS and CFAST when it comes to the highest temperatures. Additionally, compared with temperatures in tests 1-5, temperatures in test 6 are higher for both experimental tests and fire simulations, which means that having a supply opening for smoke exhaust, compared with no supply opening, can obviously reduce temperatures.



(a) smoke layer temperature in test 1 (b) smoke layer temperature in test 2 (c) smoke layer temperature in test 3



(d) smoke layer temperature in test 4 (e) smoke layer temperature in test 5 (f) smoke layer temperature in test 6

Fig. 4. Smoke layer temperatures

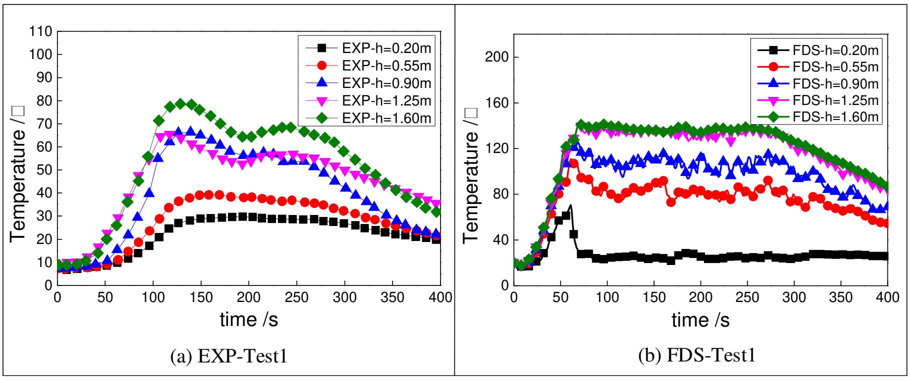
Table 3. Average and highest smoke layer temperatures for tests 1-6 during 500s

Test	Experiment, ℃	FDS, ℃	CFAST, ℃
1	54.3/68.8	99.7/135.7	82.0/111.8
2	58.8/75.0	104.6/139.9	83.1/111.6
3	61.9/89.3	103.2/137.1	82.0/110.8
4	60.9/93.2	99.9/128.1	82.8/109.6
5	64.6/82.5	99.8/127.2	82.6/103.4
6	74.3/108.0	129.3/181.8	89.4/143.9

SMOKE STRATIFICATION

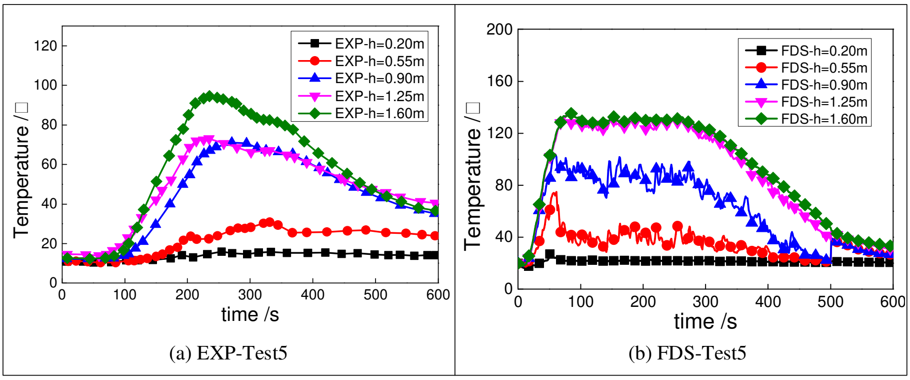
Thermocouples labeled as A1-A5, at the height of 0.2, 0.55, 0.9, 1.25 and 1.6 m above the floor, were installed to record temperatures at different heights, as shown in the Fig. 1. Temperatures measured by these thermocouples are collected to analyze smoke stratification.

Figures 5 and 6 show smoke layer temperatures at different heights for experimental test 1 and 5, respectively. As shown in the figures, temperatures measured by thermocouples at the heights of 0.20 and 0.55 m are lower than those measured by the rest of the thermocouples in the full-scale experiment. Similarly, the temperature measured by the thermocouple at the height of 0.20 m is lower than those measured by the rest of the thermocouples. The phenomenon is much more obvious in test 5 than it is in test 1 for both experiments and fire simulation by FDS.



(a) EXP-Test1 (b) FDS-Test1

Fig. 5. Smoke layer Temperatures at different heights for test 1.



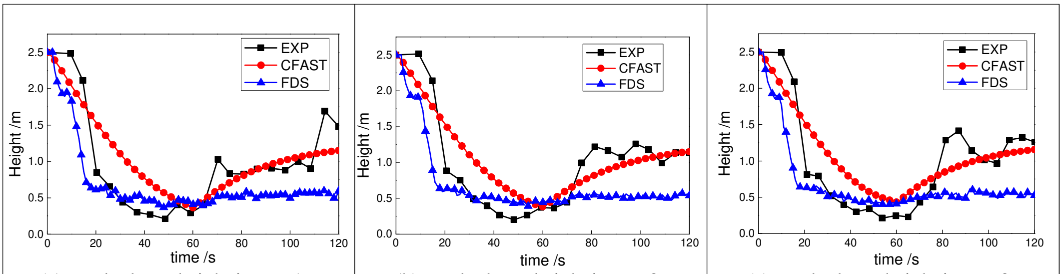
(a) EXP-Test5 (b) FDS-Test5

Fig. 6. Smoke layer temperatures at different heights for test 5.

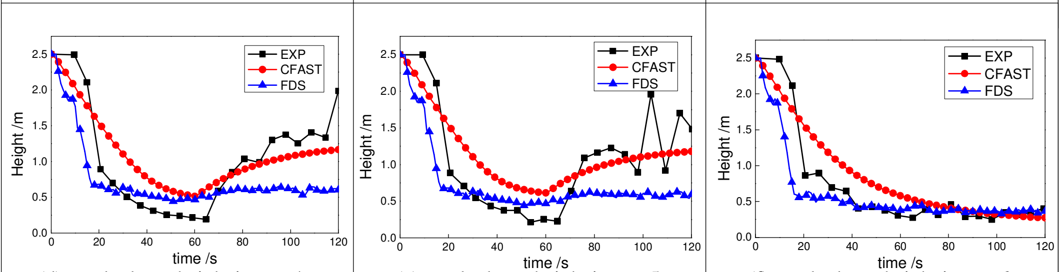
SMOKE LAYER HEIGHT ANALYSIS

The smoke layer height calculation method by Audouin and Tourniaire was used to evaluate smoke layer heights for experimental tests in this study [20]. The method is based on the assumption of a vertical temperature gradient in the hot upper region and on mathematical considerations. The results of this method are compared with the data obtained during recent experiments on forced-ventilation enclosure fires carried out in IRSN facilities and show that the method leads to good predictions of interface height and temperature profiles. Unlike two-zone model-CFAST, the smoke layer height by FDS at different locations like at the corner or in the center of the room is inconsistent at a given time due to smoke transport. Therefore, the smoke layer heights at five different locations (B1-B5) in the model cabin were collected and averaged for reporting as the smoke layer heights in this study.

The smoke layer heights for experimental tests and fire simulations by CFAST and FDS during six working conditions are shown in Fig. 7. As shown in the figure, the smoke rapidly accumulates in the cabin after fire ignition, resulting in the smoke layer descending to around 0.5 m at 20 seconds and then remaining steady at this low level until 60 seconds, after which the smoke layer rises and remains steady at a high level for tests 1-5, but still keeps at a low level for test 6. This result shows that the supply opening for smoke exhausts can obviously improve smoke layer heights. Additionally, the same trend of smoke layer heights changing over time is shown for experimental tests and fire simulations, even though some differences exist.



(a) smoke layer height in test 1 (b) smoke layer height in test 2 (c) smoke layer height in test 3



(d) smoke layer height in test 4 (e) smoke layer height in test 5 (f) smoke layer height in test 6

Fig. 7. Smoke layer heights

Table 4. Average smoke layer heights for tests 1-6

Test	Experiment /m	FDS /m	CFAST /m
1	0.86	0.69	1.06
2	0.92	0.69	1.06
3	0.92	0.69	1.08
4	0.98	0.74	1.11
5	1.00	0.74	1.14
6	0.61	0.61	0.86

Smoke layer heights recorded in 120 seconds were averaged as average smoke layer heights in Table 4. As shown in the table, average smoke layer heights in six tests 1-6 increase with the areas of supply openings increasing and the same trend is seen from the perspective of fire simulation results. Additionally, compared with average smoke layer heights in tests 1-5, the smoke layer height in test 6 is lower for both experimental tests and fire simulations, which means that having a supply opening for smoke exhaust, compared with no supply opening, can obviously improve smoke layer heights.

CONCLUSIONS

Experiments, which were compared with numerical simulations, show that natural supply openings for smoke exhausts, as opposed to no natural supply openings, can effectively reduce smoke layer temperatures and increase smoke layer heights in the experimental cabin. The data are in good qualitative agreement with numerical simulation results by CFAST and FDS.

It is also shown that there is a much more obvious smoke stratification for the conditions of test 5 than in test 1, which is due to the fact that the bigger the area of the supply opening, the smaller the air velocity through the opening, resulting in a less disturbed smoke layer by air flow.

However, a different trend is seen between fire simulation and experimental tests in terms of the effect of sizes of the supply opening on smoke exhaust effectiveness. From the perspective of experimental tests, a smaller supply opening results in a lower smoke layer temperature and smoke layer height. However, a smaller supply opening results in a higher smoke layer temperature and a lower smoke layer height from the perspectives of fire simulations. The difference exists due to the fact that it was assumed that heat release rates for fire simulations are the same in the six tests, which is actually not in accordance with the complicated burning characteristics of real cabin fire scenarios. The heat release rates for the six tested experimental conditions are not exactly the same, due to different air flow characteristics in natural supply openings. This effect leads to different combustion behavior in the six experiments, thereby resulting in different heat release rates and burning processes.

By comparison of CFAST and FDS in terms of the simulation accuracy, it is shown that CFAST has better accuracy than FDS in terms of smoke layer temperatures, while FDS has better accuracy than CFAST in terms of smoke layer heights for ship cabin fire scenarios. Both FDS and CFAST can be conservatively used for fire probabilistic safety assessment, due to the fact that their simulation results can normally be taken as conservative estimates of fire test measurements.

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