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Modeling fire-induced smoke spread and carbon monoxide transportation in a long channel: Fire Dynamics Simulator comparisons with measured data

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Abstract

Smoke and toxic gases, such as carbon monoxide, are the most fatal factors in fires. This paper models fire-induced smoke spread and carbon monoxide transportation in an 88 m long channel by Fire Dynamics Simulator (FDS) with large eddy simulation (LES). FDS is now a well-founded fire dynamics computational fluid dynamic (CFD) program, which was developed by National Institute of Standards and Technology (NIST). Two full scale experiments with fire sizes of 0.75 and 1.6 MW were conducted in this channel to validate the program. The spread of the fire-induced smoke flow together with the smoke temperature distribution along the channel, and the carbon monoxide concentration at an assigned position were measured. The FDS simulation results were compared with experimental data with fairly good agreement demonstrated. The validation work is then extended to numerically study the carbon monoxide concentration distribution, both vertically and longitudinally, in this long channel. Results showed that carbon monoxide concentration increase linearly with the height above the floor and decreases exponentially with the distance away from the fire source.

Keywords: Fire; Smoke; Carbon monoxide; Channel; Fire Dynamics Simulator (FDS)

1. Introduction

Smoke and toxic gases, such as carbon monoxide, are the most fatal factors in fires [1,2]. The smoke particles decrease the visibility range in the space resulting in that the people cannot find the way out. Also the toxic gases directly harms and kills the evacuee. Thus, the spread of the smoke and the carbon monoxide concentration level are two major concerns in fire safety risk assessment. With the rapid development of computer, it provides an efficient tool for fire safety risk assessment [3] that using of computational fluid dynamics (CFD) and in particular large eddy simulation (LES) codes to model fires. The software package, Fire Dynamics Simulator (FDS), a LES code with a post-processing visualization tool, SMOKEVIEW, developed by National Institute of Standards and Technology (NIST), USA is now a practical tool for simulating fire-induced environment. This model has been subjected to numerous validation and calibration studies on temperature and velocity field distribution in normal sized room fires [4–6]. It was also applied to study the dispersion of propane under a leakage condition in a room [7] and contamination levels in near and far field in a warehouse facility under forced ventilation [8]. However, how good the gas concentration distribution in the fire-induced smoke flow will be predicted by FDS has rarely been addressed.

Long channel fires, such as tunnel fire and long corridor fire, is a special topic in enclosure fires, due to its different aspect ratio from normal room enclosures. In tunnel fires, much more toxic gases are released due to incomplete combustion. This paper is to exam FDS in predicting the fire-induced smoke spread and carbon monoxide transportation by two case studies in an 88 m long channel.

Two full scale experiments were conducted in the channel. The spread of the fire-induced smoke flow together with the smoke temperature distribution along the channel, and the

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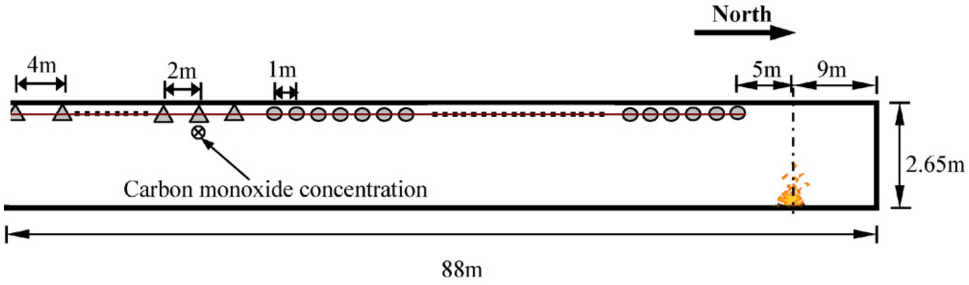
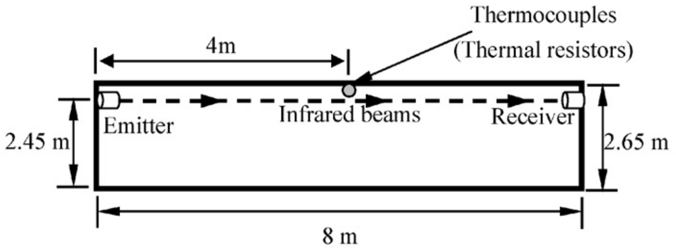


(a) Longitudinal view



(b) Cross-sectional view

Fig. 1. Dimensions of the full scale test channel.

carbon monoxide concentration at an assigned position were measured. The FDS predictions were compared with experimental data. The validation work was then extended to study the carbon monoxide concentration distribution, both vertically and longitudinally, in this long channel.

2. Experimental

Two full scale tests were conducted in an underground channel, which is 88 m long, 8 m wide and 2.65 m high. The north end was closed while the south end half-opened. The sidewalls were made of concrete and the ceiling made of gypsum. The ambient temperature was about 27.5 and 28 °C for the two tests, respectively. The schematic view of the channel and the layout of the experimental facilities are shown in Fig. 1.

Diesel pool fires were set up at floor level at about 9 m away from the north end and in the middle of the two sidewalls. The test 1 and the test 2 were conducted with pool fires of four and eight same circular pans respectively. The diameter of all pans is 0.44 m. The burning time of the pool fire was about 10 min. The heat release rates of the pool fires were measured by oxygen consumption method. The maximum steady heat release rates for these two tests are 0.75 and 1.6 MW, respectively. And in order to protect the ceiling of the long channel from burning out by the flame, a steel board sized 2 m × 3 m was placed directely above the pool fire as shown in Fig. 2. The height of the steel board was 2 m above the floor level.

Two sets of thermocouples and one set of thermal resistors were used to measure the smoke temperature distribution along the channel. The first set consisted of 23 K-type thermocouples with the first and the last thermocouple at 5 and 27 m from the fire source, respectively. The second set had 26 K-type thermocouples with the first and the last thermocouple at 29 and 54 m from the fire source. Both sets of thermocouples were positioned at 1 m intervals. There were eight thermal resistors with the first three positioned at 2 m intervals, and the other five at 4 m intervals. The first thermal resistor was 53 m from the fire source. All the thermocouples and thermal resistors were positioned at about 5 cm below the central axis of the ceiling.

Infrared beam system was installed to track the longitudinal spread of smoke flow in the channel. The design of the infrared beam system is shown in Fig. 3. A branch of infrared beams was

Fig. 2. Photo of the steel board above the fire during the full scale tests.

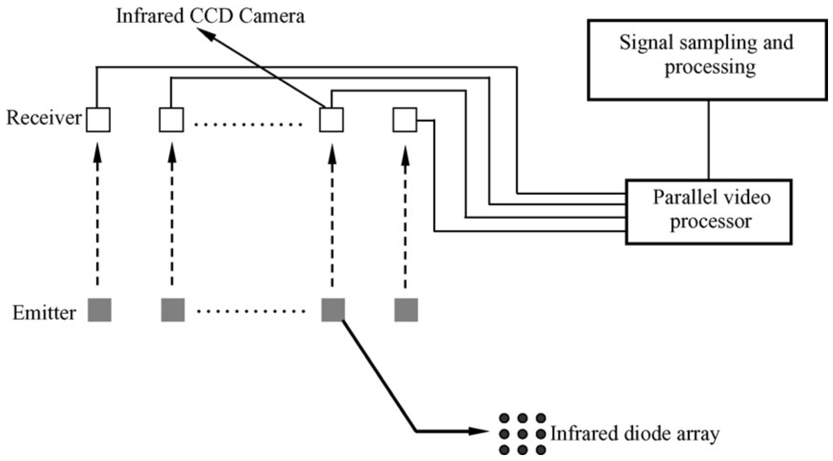


Fig. 3. Design of the infrared beam system.

launched by the emitter on one side of the wall and received by the receiver on the opposite wall. The emitter was composed of an array of infrared emitting diodes. The corresponding receiver was an infrared CCD camera. Ten pairs of infrared beams, each composed of one emitter and one receiver, were positioned at 2.45 m high from the floor. The first and last pair of infrared beams was located at 7 and 79 m from the fire, respectively. Longitudinal intervals of these infrared beams were 8 m. Typical light intensity curves recorded during test 1 are shown in Fig. 4. When the smoke flow arrived at the position of a pair of infrared beams, the intensity of a light beam passing through the smoke was attenuated by refraction, scattering and absorption due to the smoke particles. A sudden light intensity decrease resulted in.

Carbon monoxide concentration was recorded at 55 m away from the fire by a potable combustion products analyzer. The sampling probe was located in the middle of the two sidewalls with height of 2.2 m above the floor.

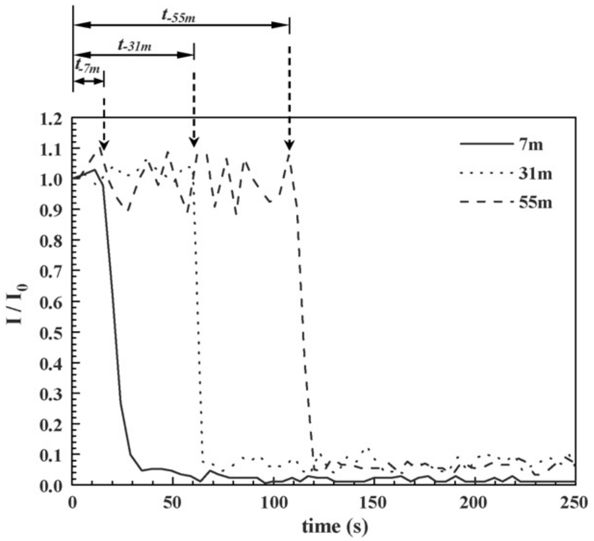


Fig. 4. Typical light intensity decay recorded by infrared beam system in the full scale tests.

3. FDS simulations

Numerical simulations were performed by Fire Dynamics Simulator (FDS). It was developed by National Institute of Standards and Technology, USA. Pool fires, with same areas as that in the tests, were set as fire sources. The heat outputs of these pool fires were set according to the heat release rate per unit area (HRRPUA) in FDS. The heat release rate history of the pool fires were set by "RAMP" command in FDS, according to that measured values for these pool fires. The heat release rate (HRR) history curve both measured and predicted by FDS for test 1 are shown in Fig. 5. It can be seen the HRR history curves predicted by FDS were close to that measured.

In FDS, a mixture fraction combustion model is used for LES simulation [6]. It is assumed that a single hydrocarbon fuel is being burned, with constant yields of CO and soot. The fraction of fuel mass converted into CO, y_{CO}, is linked to the soot yield fraction, y_{s}, via the correlation developed by Koylu and Faeth [6,9]. As diesel oil was used as fuel in the experiments, which mainly consists of hydrocarbons, the value of y_{s} was set to be 0.1 according to that of "crude oil" in FDS reaction database [6].

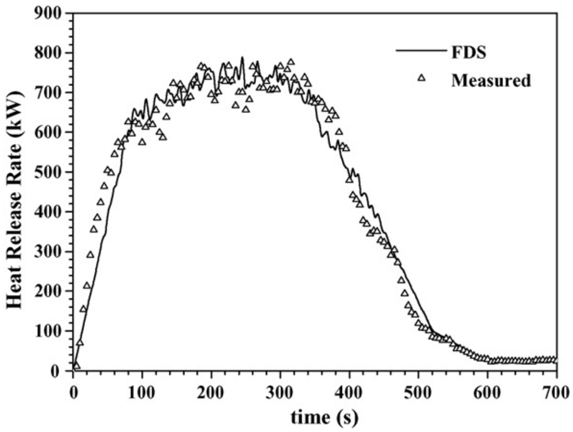


Fig. 5. Heat release rate (HRR) measured and simulated by FDS.

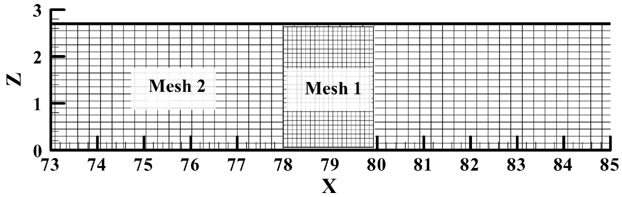


Fig. 6. Grid system for the FDS simulations.

The internal boundary material of the simulated channel was set to be same as that in the experiments. The ceiling was set to be gypsum. The side wall and the floor were set to be concrete. The properties of these two materials were just set according to the database of FDS.

The simulation domain was 88 m long, 8 m wide and 2.7 m high. The space between 2.65 and 2.7 m was filled by gypsum. Multi-mesh technology in FDS was applied. As shown in Fig. 6, mesh 1 was set as near fire plume domain, $2\,\mathrm{m}(x) \times 2\,\mathrm{m}(y) \times 2.7\,\mathrm{m}(z)$, with small grid size, $0.1\,\mathrm{m}(x) \times 0.1\,\mathrm{m}(y) \times 0.1\,\mathrm{m}(z)$ for one control volume, as complex combustion and physical process would occur in this domain. Mesh 2 was other space, $88\,\mathrm{m}(x) \times 8\,\mathrm{m}(y) \times 2.7\,\mathrm{m}(z)$, with coarse grid sizes, $0.25\,\mathrm{m}(x) \times 0.25\,\mathrm{m}(y) \times 0.15\,\mathrm{m}(z)$ for one control volume.

The temperature and CO concentration at the measurement point in the full scale experiments were predicted in FDS by "THCP" output commander. Further, the longitudinal and vertical distributions of CO concentration were also computed during the FDS simulation. The vertical distribution of CO concentration was computed in FDS simulation at 39 m away from the fire. Values were recorded at height of 2.45, 1.95, 1.45, 0.95 and 0.45 m above the floor level. The CO concentrations were computed at 10 longitudinal positions, from 7 to 79 m away from the fire with same interval of 8 m and height of 2.45 m above the floor.

All the numerical simulations were conducted in a personal computer with CPU 2.4 GHz and 1 GB RAM. All cases were run for simulation time of 600 s.

4. Results and discussion

4.1. Smoke flow spread

Fire-induce buoyancy, or the temperature difference above the ambient, is the key driver of the smoke flow. Typical smoke temperature history curves, at different distances from the fire source, predicted by FDS are shown in Fig. 7. The smoke temperature distribution along the channel predicted by FDS is compared with that measured in Fig. 8. It is shown that the temperature predicted by FDS was very close to that experimental measured data.

As also shown in Fig. 7, when the smoke flow got to an assigned position, the temperature resulted in a sudden rise. This beginning time was indicated to be the longitudinal arrival times of the smoke flow to these positions predicted by FDS. This method of judging the smoke font had been formerly validated in the literature [10]. The travel times of smoke flow to different distances from the fire predicted by FDS were compared with measured data in Fig. 9. It can be seen that the spread of smoke flow along the channel predicted by FDS was also near to that recorded in the corresponding full scale tests.

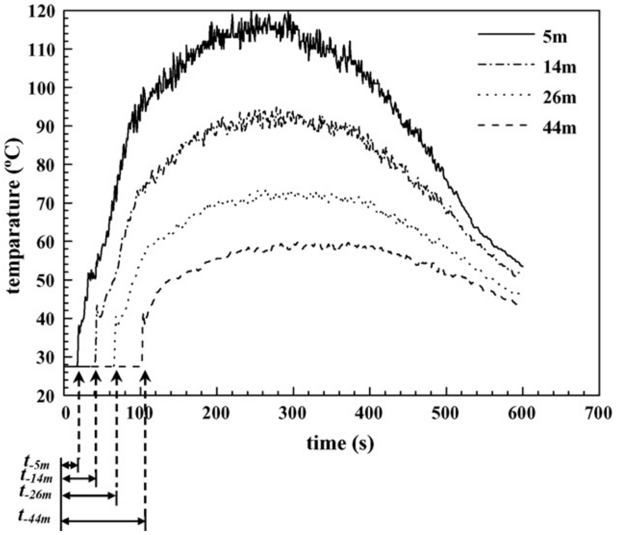
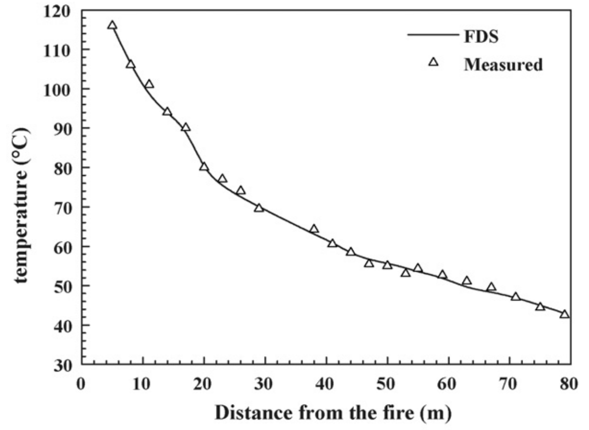
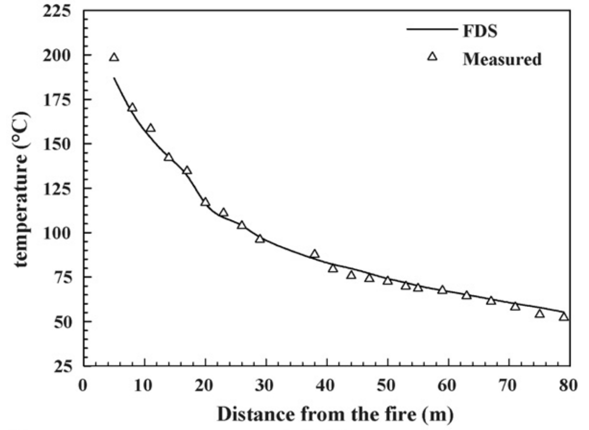


Fig. 7. Typical temperature history curves and longitudinal travel time of smoke flow predicted by FDS (test 1).

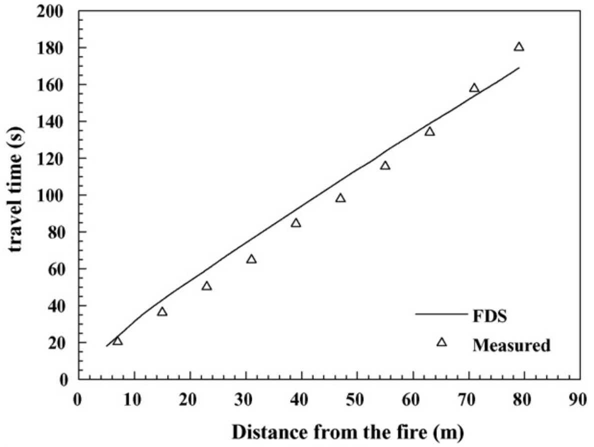


(a) 0.75MW

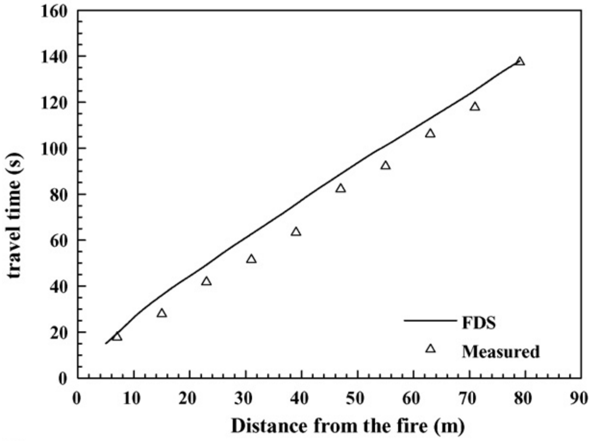


(b) 1.6MW

Fig. 8. Comparison of smoke temperature distribution along the channel predicted by FDS with measured in the full scale tests.



(a) 0.75MW



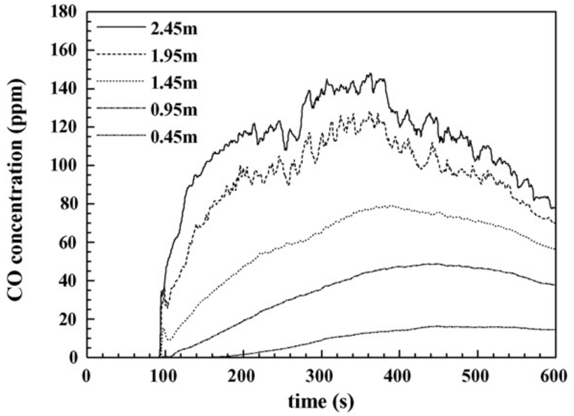
(b) 1.6MW

Fig. 9. Comparison of longitudinal travel time of smoke flow along the channel predicted by FDS with recorded in the full scale tests.

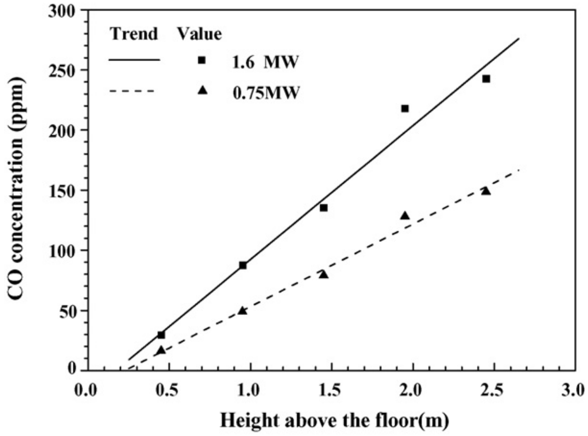
4.2. *Carbon monoxide concentration distribution*

The CO concentration predicted by FDS is compared with the measured value in Fig. 10. It can be seen FDS performs fairly well in modeling the development of CO concentration with errors less than 11%. The CO concentration predicted by FDS was slightly lower than the measured data.

The time-variation and vertical distributions of CO concentration modeled by FDS for this long channel are shown in Fig. 11. It can be seen that the CO concentration reduces with



(a) time-variation



(b) Vertical distribution

Fig. 11. Vertical distribution of CO concentration (at 39 m away from the fire).

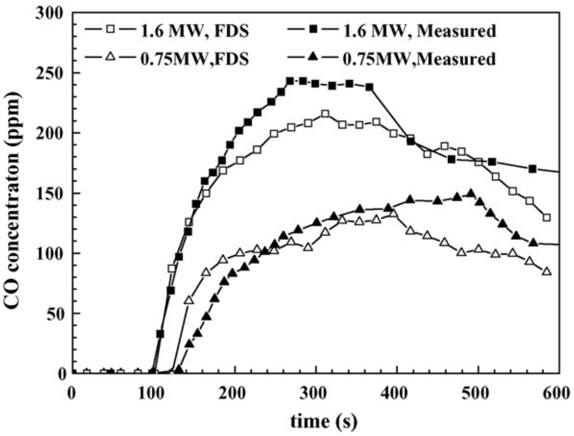


Fig. 10. Comparison of CO concentration predicted by FDS with measured data (at 55 m away from the fire, 2.2 m above the floor).

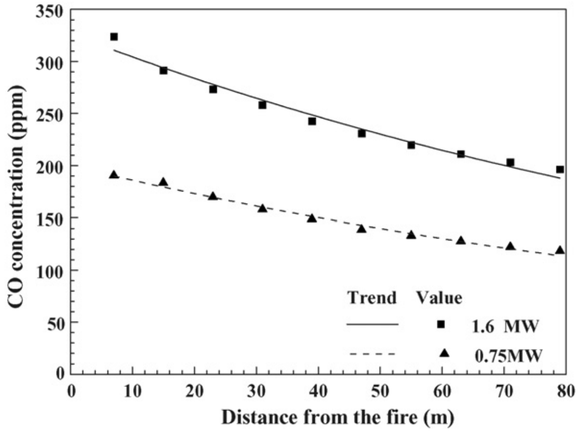


Fig. 12. Longitudinal distribution of CO concentration along the channel (height of 2.45 m above the floor).

the decrease of the height above the floor. The vertical decay of CO concentration can be well correlated by linear regression with correlation coefficient of 0.9909 (1.6 MW) and 0.99421 (0.75 MW). The longitudinal distribution of CO concentration predicted by FDS is shown in Fig. 12. The more distance away from the fire source, the lower the local CO concentration of the smoke flow. They can be well correlated by exponential regression with correlation coefficient of 0.9938 (1.6 MW) and 0.9876 (0.75 MW).

5. Conclusions

Two sets of full scale tests were conducted for validation of FDS for simulating fire-induced smoke spread and carbon monoxide transportation in an 88 m long channel. Results showed that the temperature distribution and the spread of the smoke flow predicted by FDS agreed well with the full scale measured data. The carbon monoxide concentrations predicted for these two cases were just slightly lower than the measured value. The FDS can be applied in modeling smoke spread and CO concentration distribution for fire safety assessment of such long channels. The vertical and longitudinal distributions of the CO concentration in this channel were further studied by FDS modeling. Results showed that the CO concentration would linearly increase with the height above the floor and exponentially decrease with the distance away from the fire. Study on the CO concentration at the impingement region of fire plume upon the ceiling is ongoing. It will be combined with the results of this paper to build a quantitative model to predict the CO concentration field distribution for such long channel fires.

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