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Research Article

Numerical Simulations for a Typical Train Fire in China

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Railway is the key transport means in China including the Mainland, Taiwan, and Hong Kong. Consequent to so many big arson and accidental fires in the public transport systems including trains and buses, fire safety in passenger trains is a concern. Numerical simulations with Computational Fluid Dynamics on identified fire scenarios with typical train compartments in China will be reported in this paper. The heat release rate of the first ignited item was taken as the input parameter. The mass lost rate of fuel vapor of other combustibles was estimated to predict the resultant heat release rates by the combustion models in the software. Results on air flow, velocity vectors, temperature distribution, smoke layer height, and smoke spread patterns inside the train compartment were analyzed. The results are useful for working out appropriate fire safety measures for train vehicles and determining the design fire for subway stations and railway tunnels.

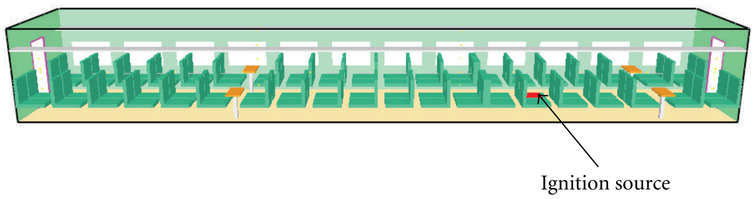
1. Introduction

Key functions of railway lines are for supporting mass transport for dense urban areas in the Far East [1], particularly important in China [2]. Traffic loadings for those railway lines in big cities are very heavy. Large number of passengers would stay inside the train vehicles for an hour. The enclosed train vehicles used to be crowded with passengers. The combustible contents can be high, depending on the train design and the luggage passengers carried. Consequent to so many accidents in public transport vehicles in the Far East, including bus fires burning up the whole vehicle within 15 minutes (e.g., [3]) and the arson underground train fires [4, 5], fire safety in the public transport systems is now a concern.

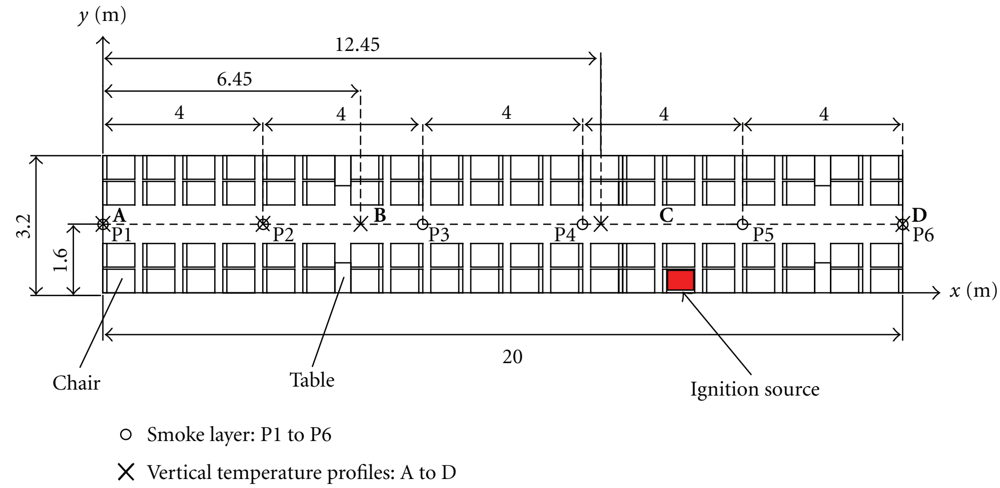
If a fire occurs, smoke and even flame would spread rapidly inside the compartment, threatening the life safety of passengers and lead to great property losses. A long list of fire safety requirements was specified for the railway systems. Whether such requirements are reasonable has to be watched. It is important to study the fire and smoke spreading inside passenger trains to ensure safe evacuation of passengers and reduce property losses.

As reviewed [6], the problems on railway system fires can be divided into train vehicles, subway stations, and railway tunnels. Train fires were studied quite extensively in the past decade. Examples are the train fire projects [7–9] in USA; those works on passenger train vehicles [10, 11] in Australia; the Daegu fire [12, 13] in Korea and the European works [14–16]. Works proposed in USA [7–9] were on fire safety design of train compartments, materials selection, design of fire detection and suppression systems, and emergency evacuation. Full-scale tests were conducted in Australia [10, 11] on fire and smoke spreading inside a passenger train. A collaboration project EUREKA [15] was set up by nine European countries from 1990 to 1992. Full-scale burning tests on a train were carried out including those tunnels [14] to study the fire size and safety, and a summary was presented [16]. Risks and possible consequences of fires in a train compartment were studied by Chow [17, 18]. Recommendations were made on the fire safety design of trains [18].

Railway transport in China (Mainland, Hong Kong and Taiwan) is developing rapidly. High-speed trains (those with travel speed over 250 km per hour) will be the key transport medium. Appropriate fire safety design has to be provided [6].



(a) Geometry



(b) Top view

Figure 1: The typical train compartment.

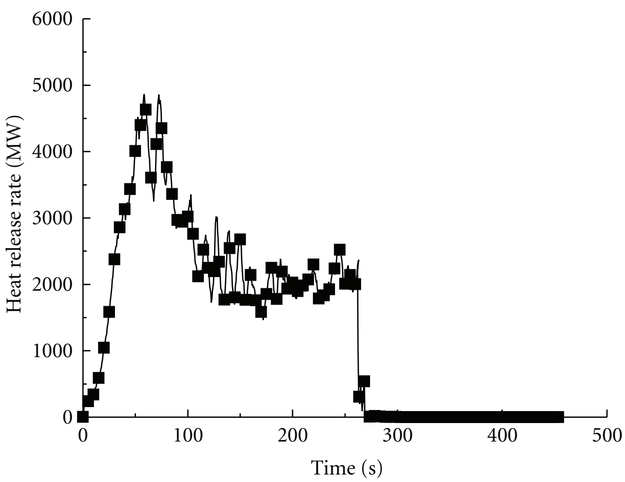


Figure 2: Predicted heat release rate in the train vehicle.

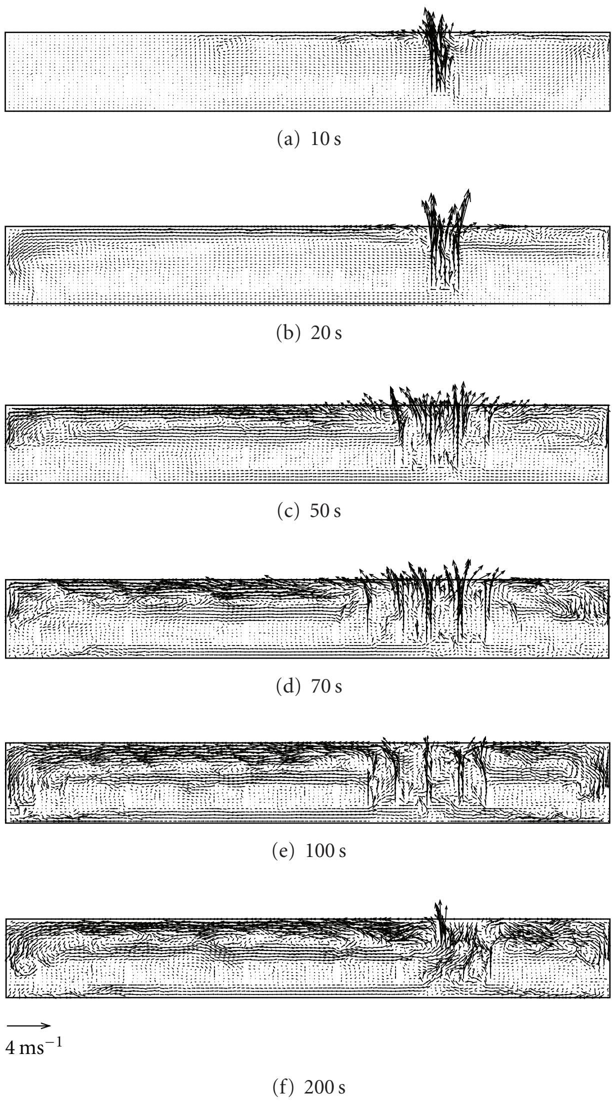
In this paper, fire environment in a train vehicle will be studied by Computational Fluid Dynamics (CFD) [19]. The model Fire Dynamics Simulator FDS 4.0.6 [20, 21] developed at the Building and Fire Research Laboratory, National Institute of Standards and Technology in USA was used. A typical train vehicle in China with two doors opened at the ends was considered. The heat release rate of the first ignited item was taken as the input parameter. Air velocity vectors, temperature distribution, smoke layer interface height, flame and smoke spread over the fire duration were predicted.

2. The CFD Model

The CFD software FDS [20, 21] was selected in this paper for simulating fires in a typical train vehicle. Smoke (including entrained air, combustion products and unburnt fuel vapor) produced from a fire is regarded as weakly combustible ideal gas flow of low Mach number. The set of Navier-Stokes equations was modified to derive the flow with filtering [22]. The turbulent part can be treated by direct numerical simulation (DNS) or large eddy simulation (LES) [19–22]. LES was adopted in this paper.

Combustion and radiation models are under development in FDS. Two combustion models can be selected, depending on the resolution of the underlying grids. Diffusion of fuel and oxygen is modeled directly for DNS with global one-step, finite-rate chemical reaction. The mixture fraction combustion model [20–23] based on the assumption of fast reaction and laminar diffusive flame is used for LES. This will resolve the diffusion of fuel and oxygen when the grids are not fine enough. In addition, the radiation absorption of gases inside the smoke layer is also considered.

In this paper, the mixture fraction model is used to describe the burning process of a fire. The model is based on the assumption that the combustion is mixing controlled.



(a) 10 s

(b) 20 s

(c) 50 s

(d) 70 s

(e) 100 s

(f) 200 s

FIGURE 3: Velocity vectors on the plane $y = 6.7$ m across the fire.

All species of interest are described by a mixture fraction $f(\vec{\mathbf{x}}, t)$. This a conserved quantity representing the fraction of species at a given point originated from the fuel. The mixture fracture $f(\vec{\mathbf{x}}, t)$ would satisfy the conservation law:

$$\frac{\partial \rho f}{\partial t} + \nabla \cdot \left(\rho \vec{\mathbf{u}} f\right) = \nabla \cdot (\rho D \nabla f). \tag{1}$$

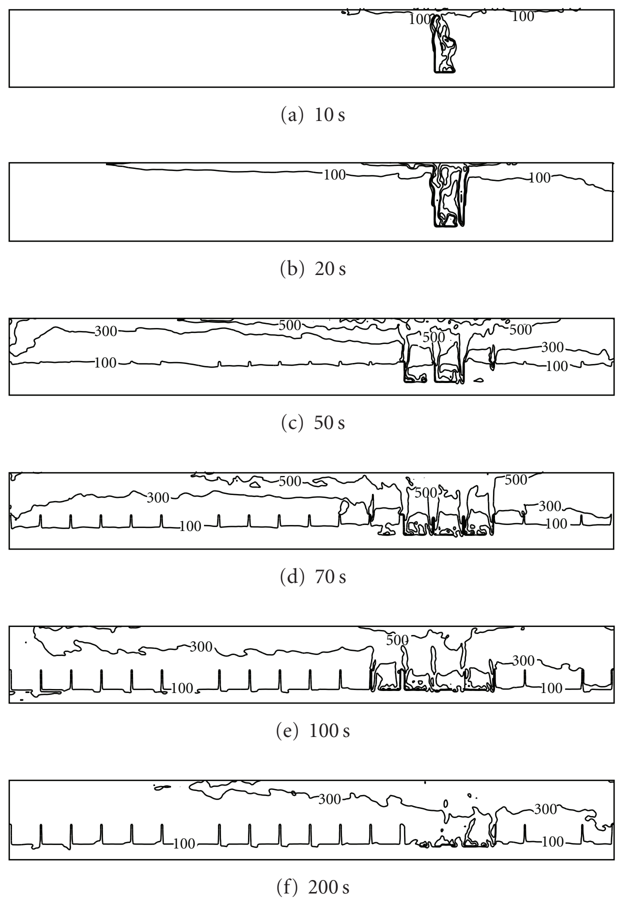
The relation between the mass fraction of each species and the mixture fraction is known as the "state relation." The state relation for the oxygen mass fraction would provide the necessary information for calculating the local oxygen mass consumption rate.

The local heat release rate $\dot{q}^m$ is computed from the local oxygen consumption rate by assuming that $\dot{q}^m$ is directly proportional to the oxygen consumption rate and independent of the fuel involved. By solving the transport equations of oxygen concentration Y_O, the mass loss rate of oxygen $\dot{m}_O^m$ can be deduced. Once the oxygen consumption rate is determined, multiplying it by the heat released per unit mass of oxygen consumed ΔH_O would give the local heat release rate $\dot{q}^m$

$$\dot{q}^m = \Delta H_O \dot{m}_O^m. \tag{2}$$

Note that deviation of the mixture fraction equation (1) is not necessarily limited to fast chemistries.

Selection of the Smagorinsky constant C_s is important in applying LES. This point had been analyzed in simulating flashover fires [24]. The value was taken to be 0.2. Both the Schmidt number Sc_T and turbulent Prandtl number Pr_T were taken as 0.5.



(a) 10 s

(b) 20 s

(c) 50 s

(d) 70 s

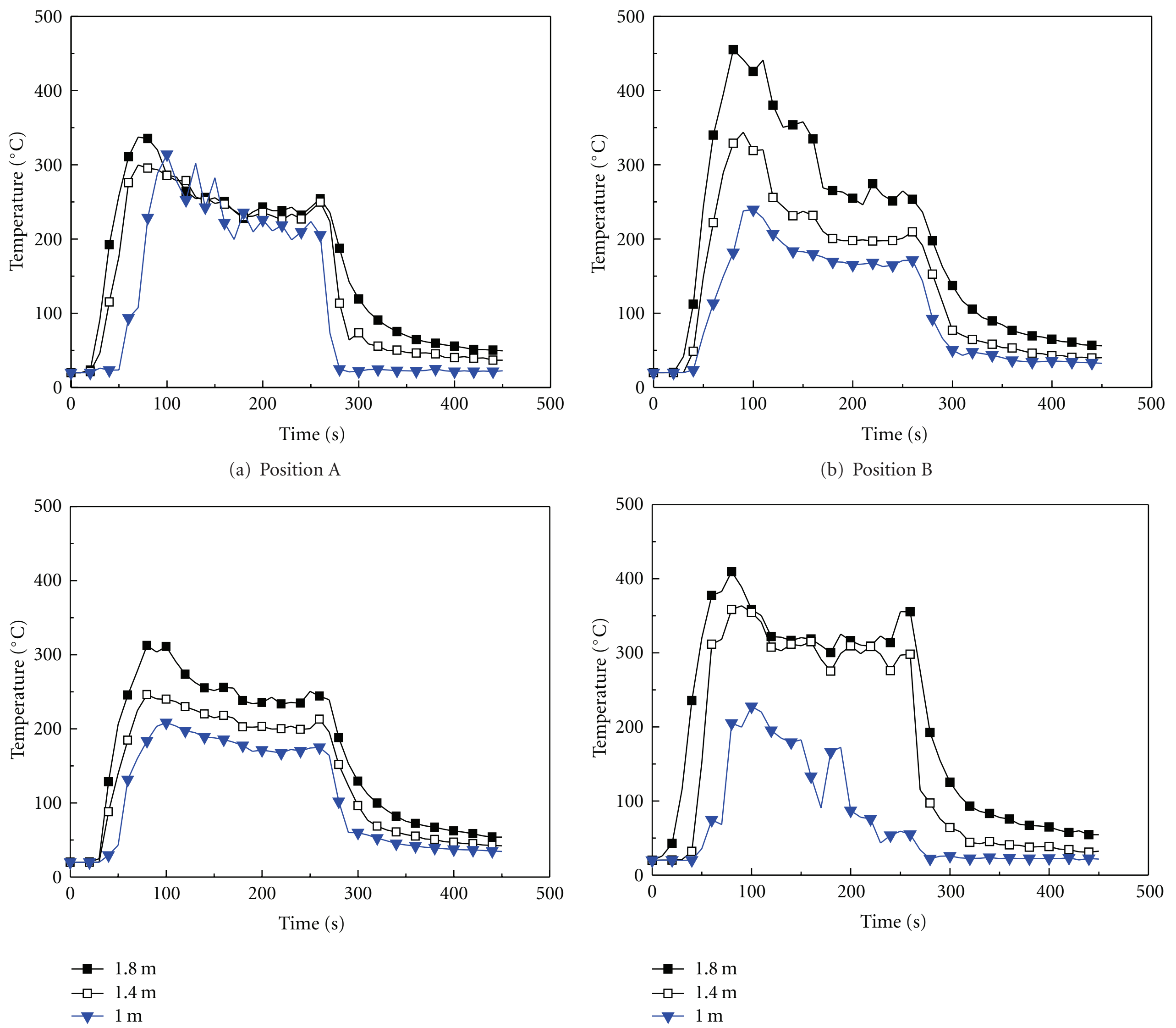
(e) 100 s

(f) 200 s

FIGURE 4: Temperature distributions on the plane $y = 6.7$ m across the fire.

TABLE 1: Combustibles inside the train compartment.

Items	Material	Number	Size
Chairs	Upholstery	20	0.8 m × 0.55 m × 0.1 m
Chair backs	Upholstery	20	0.7 m × 0.55 m × 0.1 m
Tables	Spruce	4	0.7 m × 0.4 m × 0.05 m
Table stands	Plastic	4	0.1 m × 0.1 m × 0.75 m
Luggage shelves	Plastic	2	20.0 m × 0.4 m × 0.05 m
Flooring materials	Carpet	1	20.0 m × 3.2 m



(a) Position A (b) Position B (c) Position C (d) Position D

Figure 5: Temperatures at positions A, B, C, and D.

3. Numerical Experiments

A typical train compartment in the Far East with layout and geometry shown in Figure 1 was selected. The dimensions of the train compartment are of length 20.0 m, width 3.2 m and height 2.6 m. Fire environment induced by a train fire was simulated. Location of the fire is shown in Figure 1(a). Combustibles inside the train compartment are listed in Table 1.

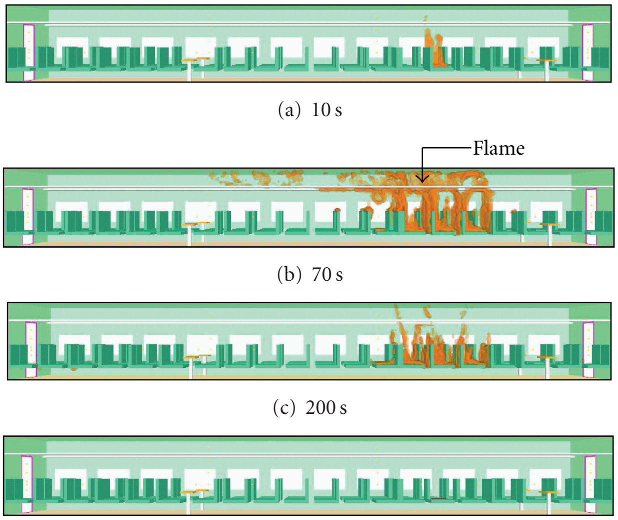
The smoke layer height was studied at points P1 to P6. Vertical temperature profiles at positions A, B, C, and D as shown in Figure 1(b) were studied. Positions A and D were along the centreline of the door above the two ends, each with six points vertically. There were five vertical points at positions B and C.

Open flame with a heat release rate of 250 kW was taken as the heat release rate of the first ignited item. The heat release rate increased linearly to a maximum value of 250 kW in 1 s, kept at this value up to 200 s and then decreased linearly to zero at 250 s.

Two opening doors were set at the two sides of the train compartment, and the open external boundaries were set. At open external boundaries, a term H expressing pressure, depending on whether the flow is outgoing or incoming is prescribed as:

$$H \begin{cases} \dfrac{|u|2}{2}, & \text{outgoing}, \\ 0, & \text{incoming}. \end{cases} \tag{3}$$

The outgoing boundary condition assumes that the pressure perturbation $\tilde{p}$ is zero at an outgoing boundary and that H is constant along streamlines. The incoming boundary condition assumes that H is zero infinitely far away. At



(a) 10 s

(b) 70 s

(c) 200 s

(d) 270 s

FIGURE 6: Flame spread inside the train compartment.

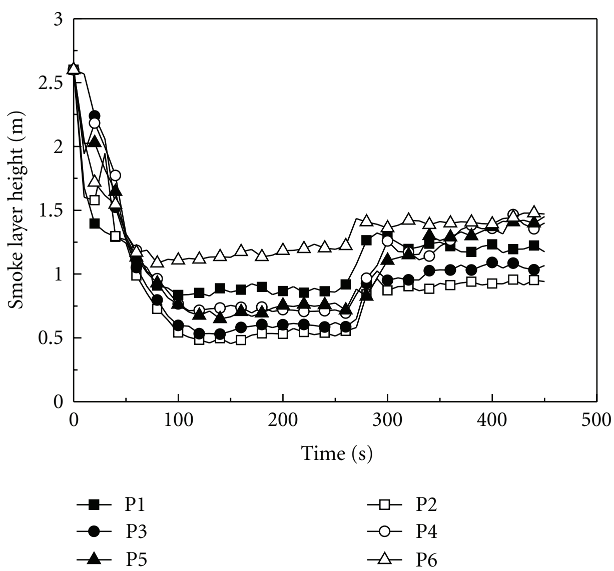
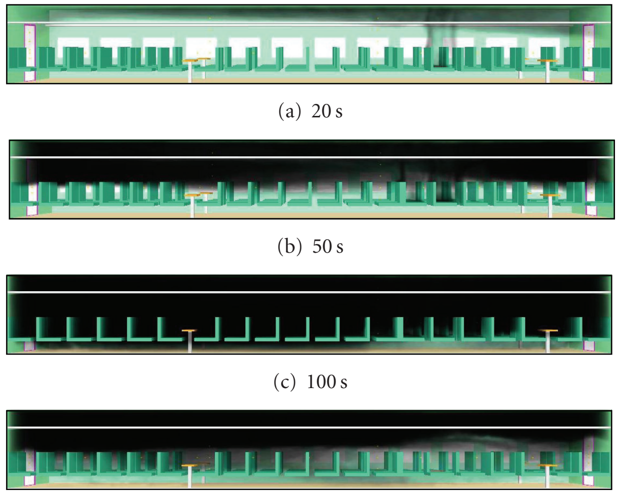


FIGURE 7: Smoke layer heights.

the boundary between two meshes, the pressure boundary condition is similar to that at an external open boundary, except that where the flow is incoming, H is taken from the adjacent mesh [20].

Other combustibles inside the train compartment would be ignited to generate heat, and then ignite more objects subsequently. The heat release rate curves inside the train compartment are shown in Figure 2. There were no other openings except the train doors at the two ends. As the combustion zone was far away from the doors, outside fresh air could not be supplied quickly. The heat release rate reached a maximum value of about 4.8 MW at 70 s. The value started to decrease to about 2 MW up to 270 s and then fell down to zero at about 270 s. Results are useful for



(a) 20 s

(b) 50 s

(c) 100 s

(d) 300 s

FIGURE 8: Smoke spread inside the train compartment.

determining the design fire [14, 16, 17] for subway stations and railway tunnels.

4. Fire-Induced Flow

Air velocity vectors at the central plane ($y = 0.9$ m) of the fire source are shown in Figures 3(a) to 3(f). The fire burnt only with a small area initially. As the fire grew up, bigger air circulation was observed until the flow reached the walls at the two ends of the train.

Temperature distribution at the central plane ($y = 0.9$ m) are shown in Figures 4(a) to 4(f). Transient temperature curves at 1.8 m, 1.4 m and 1.1 m at positions A, B, C, and D are shown in Figures 5(a) to 5(d).

It is observed from the figures that the maximum temperature at those three heights could be over 200°C. The maximum value was up to 450°C at position C near to the fire. Such high temperatures would pose risks to life. Proper safety measures should be implemented to reduce the indoor temperature.

5. Flame Spread

Both flame and smoke presented by FDS can be displayed by the postprocessor Smokeview [20, 21]. As discussed in the manual, fire by default is colored a dark shade of orange wherever the computed heat release rate per unit volume exceeds a user-defined cut-off value. This cut-off value refers to the heat release rate required at a node before calling it “fire” rather than “smoke”. Transparency or optical thickness of the fire was specified by the 50% flame depth for visualization. Taking a smaller value would give an opaque fire, and a high value would give a transparent fire.

Predicted flame spread inside the train compartment at 10 s, 70 s, 200 s and 270 s after starting to burn the first object are shown in Figures 6(a) to 6(d).

6. Smoke Spread

As observed in fire accidents, smoke spread is even more threatening than flame spread. Smoke layer height at points P1 to P6 are shown in Figure 7. Points P4 and P5 are roughly symmetric with respect to the first ignited item as in Figure 1(b). It is observed that the smoke layer height curves at points P4 and P5 basically overlapped. In view of this, data for point P4 was taken for comparison with others as in Figure 7.

As points P1 and P6 were near to the door, the smoke layer height was higher than the other three points. The smoke layer height increased with the distance away from the fire source. The smoke layer height decreased to below 1 m at all the points except for point P6. This situation would affect evacuation.

The approach to displaying smoke taken by Smokeview [19, 20] is to display a series of parallel planes, which will be colored black for smoke. The transparency value was estimated by using the time dependent soot densities computed by FDS corresponding to the grid spacings of the simulation. The transparencies are adjusted at a certain time interval to account for different path lengths through the smoke in different view directions. All the planes are combined together by the graphics hardware to form one image. The smoke "planes" might be visible under some view angles. Changing the viewing angle slightly will make the smoke appear more uniform.

The smoke spread process inside the train compartment is shown in Figures 8(a) to 8(d). As the flame spread out, the smoke layer height kept descending. When the fire was extinguished for the combustible material burnt out at 270 s, the smoke layer height started to move upwards gradually as in Figure 8(d).

7. Conclusion

In this paper, fire in a typical train compartment in the Far East was simulated using FDS 4.0.6 [20, 21]. Results indicated that serious consequences would be resulted in a train compartment fire due to the small enclosed space. Appropriate fire suppression and smoke exhaust systems should be provided to reduce the indoor temperature and keep the smoke layer high.

As flame spread depends on the materials inside the train compartment, the simulated results of temperature and smoke layer height would be different for different combustibles. Results on the heat release rate as shown in Figure 2 are also useful in determining the design fire [14–18] for subway stations and railway tunnels. Including movable fire load can give a much bigger fire than those specified in common guides [25, 26] as pointed out [16, 18].

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