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Influence of train speed and blockage ratio on the smoke characteristics in a subway tunnel

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ABSTRACT

This paper focuses on the smoke characteristics in a subway tunnel when a subway train travels between two consecutive stations at different speeds and at different tunnel blockage ratios. The piston effect caused by the train movement significantly influences the airflow in the tunnel and at the stations. To simulate the blockage effect of a vehicle and to accurately describe the smoke flow characteristics, a 3-D full-scale computational model of a subway train, two stations and a tunnel was established. To study the influence of the blockage ratio on smoke flow in the tunnel, five different cross-sectional areas were modeled. The dynamic mesh technique was used to simulate train movement in the tunnel. The results show that the maximum temperature occurs at the same position for different blockage ratios when the train runs at the same speed. The maximum temperatures in cases 2–5 decrease by 21–55% relative to the maximum temperature in case 1 at 30 s and by 11–37% relative to the maximum temperature in case 1 at 270 s. For different train speeds, the maximum temperature occurs at different positions, and the maximum temperature of all the cases is 6 to 10 times higher than that of case 6 at 30 s. The influence of train speed on the smoke movement distance is much smaller than the influence of the blockage ratio.

1. Introduction

Because of population growth and economic development, urban spaces increasingly suffer from urban traffic congestion; in response, increasing amounts of underground space are being developed to meet transportation demands (Cheng et al., 2011; Qihu, 2016; Zhao and Cao, 2011; Zhou and Zhao, 2016). Subways have become an essential means of transport in modern society. To improve transport efficiency, however, the traveling speed of subway trains must increase.

When a subway train moves through a narrow tunnel, the air in front of the lead car is pushed forward by the increase in pressure, and the air behind the tail car is drawn forward by the decrease in pressure. This phenomenon is called the piston effect, and the air flow accompanied by vehicle movement is called piston wind. Piston wind has a significant influence on the airflow in tunnels and stations. There are many factors that determine the magnitude of piston wind, with the most important factors being vehicle speed and the blockage ratio of the tunnel (Wang et al., 2014).

Most researchers have studied the effect of piston wind when a train moves in a tunnel using CFD technology or an experimental method. Bai et al. (2016) numerically and experimentally studied the pressure and velocity variation in a tunnel when a train is speeding towards a rescue station. Ko et al. (2012) performed a series of field measurements to investigate the aerodynamic pressure in tunnels induced by high-speed trains, considering the influence of train speed and the cross-sectional area (CSA) of the tunnel. Baron et al. (2001) investigated several tunnel configurations at high blockage ratios to study the aerodynamic phenomena generated by a high-speed train traveling through a long tunnel by means of quasi-one-dimensional numerical simulations. Ricco et al. (2007) experimentally and numerically (using a one-dimensional model) studied the pressure waves generated by a train entering and running through a tunnel. They found that the cross-sectional shape has little effect on the compression wave produced by the vehicle entering confined areas with the same blockage ratio. In all of the abovementioned research, the primary concern was the aerodynamic effect, whereas fewer studies have studied the influence of piston wind or the blockage ratio on smoke flow when a fire occurs in a subway tunnel or even as a subway system continues to operate during a fire.

López González et al. (2014) analyzed the influence of the piston effect in the longitudinal ventilation system of subway tunnels using numerical methodologies, considering a wide range of ventilation

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conditions and travel frequencies. Zhong et al. (2015) numerically studied smoke propagation in subway stations under the effect of piston wind and proposed three methods for reducing the effect of piston wind on smoke layers and for improving a former smoke management system. Using 3-D CFD methods, Yang et al. (2009) found that the inertial air velocity field caused by a train's movement has a significant influence on smoke diffusion in the first few minutes. Gannouni and Maad (2015) numerically studied the effect of the blocking ratio on the critical ventilation velocity and length of the backflow in the case of a vehicle located upstream of a fire source. Lee and Tsai (2012) conducted a series of experiments using a scaled tunnel model to study the critical ventilation speed under different blockage ratios and briefly analyzed the influence of the position of the fire source. Their vehicle model was relatively simple and enabled identification of the influence of piston wind and the blockage ratio on the actual movement characteristics of smoke flow.

This paper establishes a model involving a 3-D full-scale subway train, two adjacent stations and five tunnel cross-sections of different sizes. The effects of different train speeds and blockage ratios on smoke characteristics are discussed. Thus, this work lays the foundation for analyzing the ventilation control and rescue problem in subway systems in the case of a moving fire.

2. Physical model

The physical model used in this paper consists of a 6-car subway train and two platforms connected by a 1.5 km long tunnel, as shown in Fig. 1. Each platform has dimensions of 140 m × 10 m × 8 m. The train initially moves from platform1 to platform2 at a uniform speed. In this period, the train speed is the main factor affecting piston wind in the tunnel. The most common operating speed of a subway train is 70 km/h. Accordingly, the train speed is set to 50 km/h, 60 km/h, 70 km/h or 80 km/h for the different tests. Next, a fire breaks out in one of the carriages, and the train starts to brake with a deceleration of $-1\ \mathrm{m/s^2}$. At that time, the flow field in the tunnel is influenced by the piston effect and buoyancy effect. The train is assumed to be damaged such that it cannot reach platform2 and is forced to stop in the center of the tunnel (X = 750 m). To reduce the computational time, the original position of the train is set to X = 350 m to ensure the stability of the airflow. Separated by the position of the fire source, the zone located in the train's running direction is the downstream side, and the other direction is the upstream side. The fire source is set beneath the first carriage, and the fire moves along with the train. The fire lasts 4 min, corresponding to the time required to wait for rescue after stopping. Nine scenarios are investigated in this paper, as shown in Table 1.

To realistically simulate the blockage effect of a vehicle and realistically describe the smoke flow characteristics, a 1:1 3-D subway train consisting of 6 cars is used in this study, as shown in Fig. 2. The model train has a length of 117 m, and the CSA of the vehicle body is $9.276\ \mathrm{m^2}$. Certain components, e.g., the bogie, apron, head, windshield, and equipment cabin, which have a strong influence on the flow of smoke, are modeled in detail.

Table 1
Fire scenarios.

Study goal		Train speed (km/h)	Blockage ratio
Influence of the blockage ratio	Case 1	70	0.427
	Case 2	70	0.407
	Case 3	70	0.387
	Case 4	70	0.371
	Case 5	70	0.355
Influence of the train speed	Case 6	50	0.427
	Case 7	60	0.427
	Case 8	70	0.427
	Case 9	80	0.427

To study the influence of the blockage ratio on the smoke flow in the subway tunnel, five different sizes of the cross-section of the tunnel are modeled, as shown in Fig. 3. The original CSA of the tunnel is $21.7\ \mathrm{m^2}$, which is the actual value used in practice, and the other CSA values considered in the model increase in 5% increments. Thus, the blockage ratio of the implemented subway tunnel model is set to 0.427, 0.407, 0.387, 0.371 and 0.355.

3. Numerical model

This study adopts the commercial code Fluent6.3.26 to conduct the numerical simulation. The fire-smoke flow control equations used in this paper are based on 3-D, compressible, unsteady Navier–Stokes equations combined with an RNG $k-\varepsilon$ turbulence model (Fluent Inc, 2006).

3.1. Computational grid

A tetrahedral mesh is used throughout this study. Because the model length extends nearly 1.8 km, to reduce the number of elements, the mesh size is set according to the principle of combining sparseness with compactness. The grid is refined in certain complex areas of the surface shape, such as the bogie, head, air-conditioning unit, equipment cabin, corridor between carriages, and the area near the fire source with a large temperature gradient; other regions of the grid away from the car body are built at certain growth factors, gradually thinning. The size ranges from 0.04 m to 0.1 m (Ingason et al., 2014). The number of elements is approximately 7 million. Because of the enormous size of the grid and the high computing speed and memory capacity required, it is difficult for an ordinary computer to perform the calculations. Therefore, all of the calculations are conducted on the Guangzhou Tianhe-2 Supercomputer. The supercomputer combines a number of CPU and memory elements in parallel method to achieve very high computing speeds and an enormous memory capacity.

As dynamic mesh technology is used to simulate the movement of the train, to ensure the grid quality around the train during motion, the time step cannot be too large; otherwise, grid distortion will occur, resulting in the appearance of negative volume. In this research, the smallest element size is 0.04 m, and the highest train speed is 80 km/h. According to the formula (1) described in Section 3.2, the time step can

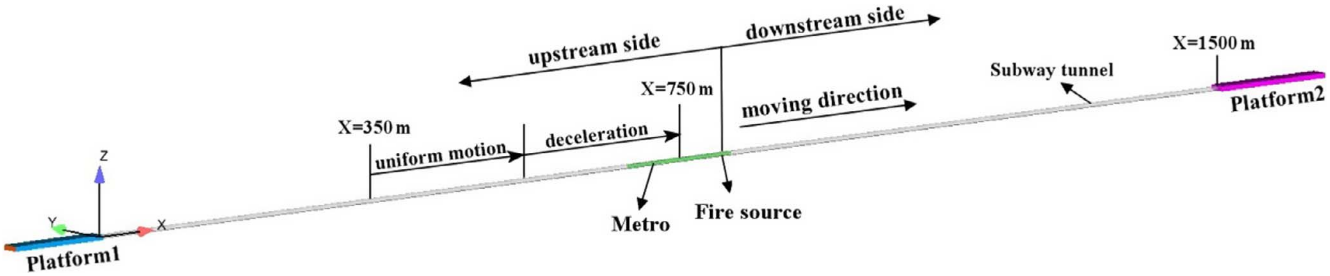

Fig. 1. Physical model.