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Numerical study of natural ventilation in urban shallow tunnels: Impact of shaft cross section

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ABSTRACT

Natural ventilation with vertical shafts uses less energy and occupies less space in a tunnel, compared to mechanical ventilation. Therefore, this natural ventilation mode has been adopted in more and more urban tunnels. This study analyzed the influence of cross-sectional area and aspect ratio (ratio of length to width) of the shaft on natural smoke exhaust in a tunnel fire, and 33 cases were simulated using the Fire Dynamics Simulator software. The temperature distribution, velocity vector field, and mass flow rate of gas exhausted by the shaft were investigated in detail. The results show that when the aspect ratio is less than 0.75, the mass flow rate of exhausted gas decreases slightly with the increase of aspect ratio, and when the aspect ratio is greater than 0.75, the mass flow rate of gas does not change obviously. With the increase of aspect ratio, the plug-holing becomes more obvious. With the increase of cross-sectional area, there is initially no plug-holing or slight plug-holing inside the shaft, but an obvious plug-holing is developed gradually, and the air penetration phenomenon with some fresh air being exhausted directly occurs finally. The mass flow rate per cross-sectional area of gas exhausted by the shaft decreases with the increase of cross-sectional area.

1. Introduction

Urban underground transit is one of the ways to alleviate the problem of traffic congestion. Underground tunnels can bring tremendous conveniences to improve the traffic efficiency and mobility (Du, Yang, Peng, & Xiao, 2015; Guan, Zhang, & Liu, 2018; Wang & Li, 2018; Yang, Zhang, & Xia, 2018). However, their fire safety problems are getting more and more attention (Ji, Bi, Venkatasubbaiah, & Li, 2016; Tang et al., 2017; Xu, You, Kong, Cao, & Zhou, 2017; Yang, Ding, Du, Mao, & Zhang, 2018). Underground tunnels are confined spaces, thus in the event of a fire, the rapid spread of toxic gases, such as carbon monoxide and hydrogen cyanide, is the main cause of casualties (Ji, Wan, Li, Han, & Sun, 2015; Jiang, Liu, Wang, & Li, 2016; Liang, Li, Li, Xu, & Li, 2017; Yan, Zhu, Woody Ju, & Ding, 2012; Zhang et al., 2016; Zhu, Shen, Yan, Guo, & Guo, 2016). Therefore, only a rapid and effective discharge of smoke can ensure the reduction of casualties in a tunnel fire.

Currently, ventilation modes mainly include mechanical ventilation (Chen, Hu, Tang, & Yi, 2013; Weng, Lu, Liu, & Du, 2016; Yi, Niu, Xu, & Wu, 2013; Yu, Liu, Liu, Weng, & Liao, 2018) and natural ventilation (Fan, Ji, Gao, Han, & Sun, 2013; Harish & Venkatasubbaiah, 2014; Tanaka, Kawabata, & Ura, 2016; Zhong et al., 2016; Zhu et al., 2015). Mechanical ventilation relies on the force generated by the fans to facilitate air circulation inside and outside the tunnel, which can effectively control the spread of smoke (Tang, Li, Mei, & Dong, 2016; Yao et al., 2016). However, it takes up some tunnel space and consumes a lot of energy, and its initial investment and maintenance costs are higher than natural ventilation. Mechanical ventilation also produces noise and requires technical staff for repair. Conversely, natural ventilation utilizes the buoyancy of smoke to make it exhaust through shafts or openings, which costs less and occupies less space in a tunnel. Therefore, the natural ventilation mode with vertical shafts has been adopted in more and more urban tunnels, such as the Chiba section of the Tokyo Outer Ring Road in Japan (Baek, Sung, & Ryou, 2017; Jin, Jin, & Gong, 2017; Kashef, Yuan, & Lei, 2013; Tanaka, Kawabata, & Ura, 2017; Wang et al., 2015; Yao, Zhang, Shi, & Cheng, 2017).

The number, location, cross-sectional form, cross-sectional area, and surrounding environment of the shaft may affect the natural smoke exhaust. At present, there are relatively few studies in this field. Yao

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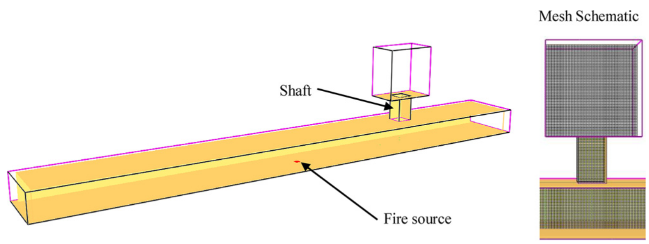

Fig. 1. Model configuration.

Table 1
Summary of all cases.

No.	A (m^2)	a	No.	A (m^2)	a	No.	A (m^2)	a
1	4	1/4	12	9	1/4	23	16	1/4
2	4	1/3	13	9	1/3.2	24	16	1/2.9
3	4	1/2.3	14	9	1/2.3	25	16	1/2.5
4	4	1/1.8	15	9	1/1.9	26	16	1/1.8
5	4	1/1.4	16	9	1/1.4	27	16	1/1.3
6	4	1/1	17	9	1/1	28	16	1/1
7	4	1.4/1	18	9	1.4/1	29	16	1.3/1
8	4	1.8/1	19	9	1.9/1	30	16	1.8/1
9	4	2.3/1	20	9	2.3/1	31	16	2.5/1
10	4	3/1	21	9	3.2/1	32	16	2.9/1
11	4	4/1	22	9	4/1	33	16	4/1

et al. (2017) studied the effect of shaft inclination angle and shaft height on the capacity of smoke exhaust. Their conclusion is that the best shaft inclination is 76°. In addition, some scholars have studied the effects of shaft cross section (Ji, Han, Fan, Gao, & Sun, 2013) or tunnel cross section (Baek et al., 2017) on natural smoke exhaust. Baek et al. (2017) experimentally investigated the effects of heat release rate and tunnel aspect ratio on the plug-holing phenomena (some ambient fresh air beneath the smoke layer being exhausted directly from the ceiling vent) in a reduced-scale model tunnel. The plug-holing phenomena was analyzed to develop a modified Froude number considering the tunnel and shaft geometrics and the heat release rate of fire. Ji, Han et al. (2013) studied the effects of cross-sectional area and aspect ratio (ratio of length to width) of the shaft on a tunnel fire with natural ventilation. Specifically, they studied the effects of the shaft width or length on the smoke exhaust, while keeping the other one of the two parameters unchanged. However, until now, for cases with an unchanged cross-sectional area of shaft, how the cross-sectional shape and aspect ratio of the shaft influence the smoke exhaust has not been revealed.

The objective of this study is to evaluate the impact of shaft aspect ratio and cross-sectional area on natural ventilation. Specifically, the effects of shaft cross section on the smoke exhaust was studied using Fire Dynamics Simulator (FDS). First, the cross-sectional area was unchanged to study the effects of aspect ratio on the smoke exhaust. Then, the aspect ratio was unchanged to study the effects of cross-sectional area. Specifically, the smoke exhaust performance of the shaft during the process of changing the aspect ratio from 0.25 to 4 with the cross-sectional areas of 4, 9, and 16 m^2 were studied. This research can provide a reference for the selection of shaft cross-sectional area and aspect ratio in practical tunnel engineering, and also enrich the knowledge of horizontal and vertical smoke movement in both tunnel and high-rise building fires (Du, Yang, Wei, & Zhang, 2018; He et al., 2018; Jiang, He, & Sun, 2018; Zhou, Bu, Gong, Yan, & Fan, 2018).

2. Numerical modeling

In this study, the characteristics of smoke spread inside a tunnel with natural ventilation were investigated by the numerical modeling software, FDS 6 (Mcgrattan et al., 2012, 2013). The model has been subjected to numerous validations, calibrations, and studies on the temperature and velocity fields in fires (Tilley & Merci, 2009; Wen, Kang, Donchev, & Karwatzki, 2007). There are also some related studies on tunnel fire under natural ventilation using shafts (Cong, Wang, Zhu, Jiang, & Shi, 2017; Fan, Ji, Wang, & Sun, 2014; Ji, Gao Fan, & Sun, 2013; Zhong, Fan, Ji, & Yang, 2013).

The tunnel model was set as 100 m long, 10 m wide, and 5 m high, and the shaft was 5 m high, as shown in Fig. 1. The natural ventilation shafts are usually built in shallow-buried urban tunnels, and the shaft height is equal to the distance between the shaft bottom and the ground. The shaft top is generally surrounded by green belts.

Additional computational regions were added near the top opening of the shaft and tunnel portals. The extended computational region added near the tunnel portals was specified as 1 m long, 12 m wide, and 5 m high, and the computational region added near the top opening of the shaft was specified as 10 m long and 10 m high. The tunnel portals and the region above the shaft were all set to be naturally opened with no initial velocity boundary condition specified, to mimic the open space condition taking into account the bidirectional flow of hot and ambient gases.

The fire source was located at the center of the tunnel and designed to follow a heat release rate of 3 MW to represent the typical scenario of a car fire, as vehicles with dangerous chemicals or heavy goods are prohibited from passing through urban tunnels. A vertical shaft was positioned at the right side of the fire with a distance of 25 m. The ambient pressure was set as 101 kPa. The material of the tunnel construction was specified as “CONCRETE”, and its density, conductivity, and specific heat were 2200 kg/m^3, 1.2 W/(m K) and 0.88 kJ/(kg K). The ambient temperature was set as 20 °C and the mesh size was set as 0.167 m in all cases.

Before conducting this study, we investigated some practical shallow urban tunnels with installed shafts. The shafts in these tunnels are commonly a cuboid with a rectangular cross section. The cross section of the shaft opening is 3.2 m long and 2.6 m wide with the aspect ratio of 1.23 in the Xianmen road tunnel in Nanjing of China, and the cross section of the shaft opening is 10 m long and 2.5 m wide with the aspect ratio of 4 in the shallow-buried intersection tunnel of Chengdu Metro of China. Overall, the cross-sectional area is in the range of 8–20 m^2 and the aspect ratio is in the range of 0.3–4 in actual engineering designs. In order to comprehensively study the effects of aspect ratio (a, ratio of shaft length to shaft width) with an unchanged cross-sectional area (A) on the natural smoke exhaust through the shaft, the cross-sectional area in this study was set as 4, 9, and 16 m^2, respectively. For each area, there were 11 aspect ratios. Table 1 lists the parameters of the 33 cases in this work. In each case, at the top opening of the shaft, a measuring point was arranged to collect the mass flow rate of gas exhausted from the shaft.

Some previous studies (Fan et al., 2018; Tanaka et al., 2016, 2017) have shown that the effect of wind outside the tunnel will influence the ventilation performance. In this study, the two key parameters, namely cross-sectional area and aspect ratio of the shaft, are studied systematically to reveal their influences in detail. Therefore, a windless environment (Wan et al., 2018) is considered here. The effect of outside weather condition should be studied further in future work.

3. Results and discussion

The simulation results were analyzed in two aspects. Firstly, the influences of different aspect ratios (1/4–4/1) on the smoke exhaust with an unchanged cross-sectional area (9 m^2) were analyzed. Secondly, the influences of different cross-sectional areas (4, 9, and 16 m^2) on the smoke exhaust with an unchanged aspect ratio (1/4, 1/1,