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Smoke spread characteristics inside a tunnel with natural ventilation under a strong environmental wind

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ABSTRACT

In order to investigate the effect of strong environmental wind on a tunnel fire under natural ventilation, a series of numerical simulations were conducted using large eddy simulation method in this study. A tunnel model was established by a numerical simulation software, Fire Dynamics Simulator, to investigate the smoke movement under the stack effect induced inside a shaft. Four environmental wind speeds (39 m/s) and three heat release rates (3–20 MW) were considered. The smoke spread velocity inside the tunnel, downdraught phenomenon at the early stage of fire, smoke exhaust characteristics at the steady period of fire, temperature distribution in the tunnel and shaft, and occurrence of plug-holing were studied in detail, based on some typical characteristic parameters, such as mass flow rate, temperature and velocity vector. The results can be considered as a reference for the fire protection design of a tunnel with natural ventilation.

1. Introduction

Fire is one of the most serious traffic accidents which happen in tunnels (Caliendo et al., 2012; Hsu et al., 2017; Santos-Reyes and Beard, 2017; Shaw et al., 2016; Tang et al. 2016). Recently, several fires caused by spontaneous combustion or collision of vehicles happened in tunnels all over the world (Meng et al., 2012; Sun et al., 2016; Yan et al., 2017). These tunnel fires not only led to a lot of casualties and severe damages of main or subsidiary structure of tunnels, but also resulted in a regional traffic paralysis and disruption of communication system, along with immeasurable indirect losses.

The most important reason why so many people get injured or die in a tunnel fire is the toxic smoke generated during combustible burning (Gao et al., 2016), so setting an effective ventilation system is quite important to control the spread of toxic smoke (He et al., 2018; Migoya et al., 2011; Tsai et al., 2011). However, the narrow structure of tunnel greatly limits the capacity of ventilation, once a fire occurs.

In general, the tunnel ventilation system can both exhaust the smoke when a fire occurs and dilute exhausting gas concentration from automobiles when the tunnel is normally operated. In recent years, many scholars conducted a lot of studies on controlling the smoke in tunnel fires. In these studies, they mainly focused on two kinds of ventilation modes, namely mechanical ventilation (Du et al., 2015; Ingason et al., 2012; Wang et al., 2012; Yao et al., 2016; Yi et al., 2013) and natural ventilation (Chen et al., 2016; Weng et al., 2014; Zhong et al., 2016).

With regard to mechanical ventilation, longitudinal ventilation with jet fans (Cascetta et al., 2016; Eftekharian et al., 2014; Li et al., 2016; Tang et al., 2017a; Zhang et al., 2012) and transverse ventilation (Jiang et al., 2016; Liang et al., 2017; Tang et al., 2017b; Yu et al., 2018) are commonly employed to exhaust the fire-induced smoke. These modes can ensure the security of evacuation, meanwhile, the external environment will not affect the effectiveness of mechanical ventilation evidently. However, such a mechanical ventilation system requires a substantial amount of electric power supply and economic support. Moreover, longitudinal ventilation can easily disturb the smoke stratification, and thus is unfavorable to evacuate people at the early stage of fire.

Compared with mechanical ventilation, natural ventilation affects the smoke layer propagation slightly. Buoyancy-driven natural ventilation can exhaust the smoke through a shaft or other openings installed on the tunnel ceiling (Harish and Venkatasubbaiah, 2014; Jin et al., 2017; Wang et al., 2015). Stack effect will be induced by the smoke temperature differences in a shaft from the ground surface to the transit tunnels. In China, natural ventilation with shafts was employed for the first time in Chengdu metro. Nowadays, natural ventilation is gradually

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Table 1
Wind speed classification.

Wind level	Name	Wind speed, m/s
0	Calm	0.0–0.2
1	Light air	0.3–1.5
2	Light breeze	1.6–3.3
3	Gentle breeze	3.3–5.4
4	Moderate breeze	5.5–7.9
5	Fresh breeze	8.0–10.7
6	Strong breeze	10.8–13.8
7	Moderate gale	13.8–17.1

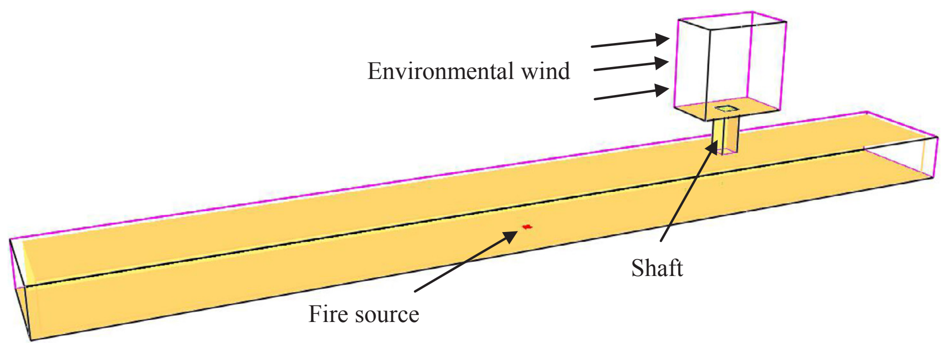


Fig. 1. Model configuration.

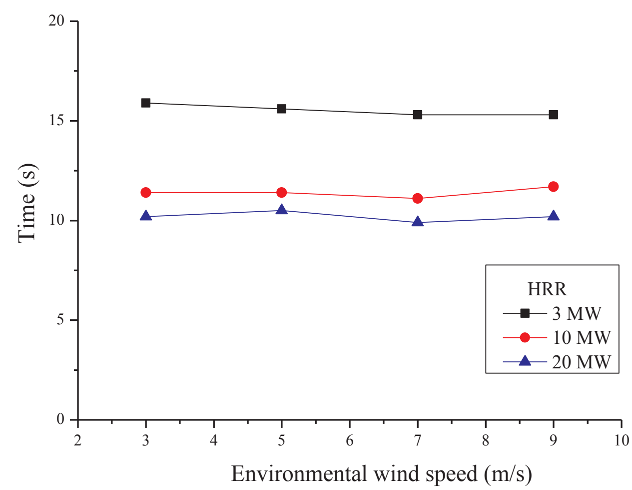
used in tunnels, because of its economic efficiency and easy operation. Therefore, it becomes one of the focuses in the research of tunnel ventilation modes in recent years, especially the spread characteristics of smoke under natural ventilation shafts.

Some scholars have already studied the effectiveness of natural ventilation when the environmental wind outside the tunnel cannot be overlooked (Tanaka et al., 2016, 2017; Wang et al., 2009). However, the wind speed in these studies is not high enough to reflect the natural situation in case of a strong wind, as the maximum is about 3 m/s in these previous studies. Stronger wind may not anymore follow the theoretical variation predicted by previous literature or bring some unpredictable effects including an extremely negative effect on smoke exhaust by natural ventilation. Table 1 shows the wind speed classification based on China meteorological administration. Moreover, based on statistical data, the average annual wind speed in urban area of Shanghai is around 2.8 m/s, while it is about 2.5 m/s in urban area of Beijing. However, in the extreme weather with a stronger wind, moderate breeze or fresh breeze may exist with the environmental wind speed being about 10 m/s.

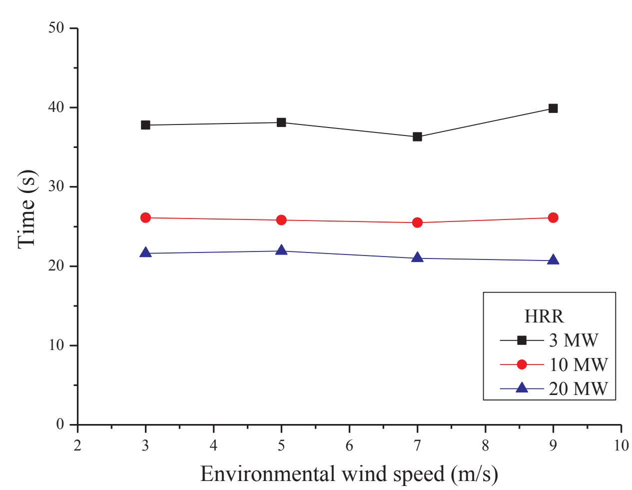
In this study, the effect of strong environmental wind (ranging from 3 to 9 m/s) on natural ventilation in tunnels was investigated in detail. A fire simulation software, FDS (Fire Dynamics Simulator), was used to build the tunnel model and simulate the cases with different

Table 2
Summary of all cases.

No.	Heat release rate (MW)	Environmental wind speed (m/s)
1	3	3
2	3	5
3	3	7
4	3	9
5	10	3
6	10	5
7	10	7
8	10	9
9	20	3
10	20	5
11	20	7
12	20	9



(a) Time when smoke spreads to 25 m downstream of the fire.



(b) Time when smoke spreads to 50 m downstream of the fire.

Fig. 2. Characteristics of smoke spread downstream of the fire.