Effect of inclined mainline on smoke backlayering length in a naturally branched tunnel fire

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Abstract

In this study, the effect of the slope of the mainline tunnel on the characteristics of smoke movement and the distance of smoke backflow in a branched tunnel with an inclined downstream mainline was investigated. The downstream mainline tunnel slope varied from 0% to 7% at intervals of 1%. A virtual wind velocity was proposed as a means to correlate with the airflow velocity induced by the stack effect. The results showed that a significant airflow velocity was formed in the branched tunnel with an inclination of the mainline before shunting. When the tunnel slope and fire size were larger, the induced airflow velocity was enhanced due to the greater thermal pressure difference induced by the stack effect. The effect of the bifurcation angle on induced airflow velocity was limited, but could not be neglected under relatively large heat release rates. The smoke was well controlled into the horizontal mainline region due to the induced wind by the stack effect. The backlayering length was slightly reduced under stronger heat release rates but was more sensitive to the slope of the mainline tunnel. A prediction model for smoke backlayering length in a branched tunnel with a tilted downstream mainline was developed based on dimensionless velocity. The predicted value of the smoke backlayering length agreed well with the simulated results. This study contributes to the understanding of smoke movement in naturally branched tunnels with inclined downstream sections and guides extraction design.

Keywords: tunnel fire, tunnel slope, backlayering length, bifurcation angle, natural ventilation

1. Introduction

Nowadays, tunnel fire accidents have occurred and resulted in serious casualties. The Taojiakuang tunnel fire in China resulted in 12 deaths and 1 serious injury in 2017. The Yanhou tunnel fire accident in China resulted in 40 deaths and 12

Nomenclature

		U	coefficient
a	coefficient	$u_{up,max}$	maximum velocity of smoke at upstream (m/s)
b	coefficient	V'	virtual velocity (m/s)
c_p	specific heat (J/ (kg·K))	v	trajectory velocity of plume (m/s)
C, C_1, C_2, C_3, C_4	coefficient	x	distance to fire source (m)
D^*	characteristic fire diameter	*Greek symbols*	
d, d_s	hydraulic diameter of tunnel and reverse smoke layer (m)	$\triangle$	difference
g	gravitational acceleration (m/s^2)	ρ_∞, ρ_s, ρ_j	ambient density, smoke density, density at beginning reverse flow position (kg/m^3)
H	tunnel height (m)	α	included angle between plume axis and tunnel floor surface (°)
h	elevation difference (m)		
L	inclined mainline tunnel length (m)	β	inclination angle of mainline tunnel (°)
l	tunnel projection distance of inclined region(m)	δ	entrainment coefficient
m, n	power coefficients	η	entrainment coefficient
$P_{stack,d}$	stack pressure (Pa)	λ	frication coefficient
Q, Q_m	heat release rate, effective heat release rate in mainline (kW/m^2)	*Subscripts and Superscripts*	
		∞	ambient condition
r	radius of plume (m)	s	smoke
T, T_∞	smoke temperature, ambient temperature (K)	up	upstream
T_j	temperature at j (K)	j	beginning reverse flow position
$\triangle T$	temperature difference (K)	$stack,d$	stack effect at downstream

injured in 2014. The accumulation and propagation of smoke in the tunnel mainly threaten personal evacuation. Recently, with the development of urban underground transportation, the inclined tunnel has been extensively constructed. Many previous studies on tunnel fire have focused on smoke propagation in an inclined tunnel. Atkinson and Wu (1996) claimed that the critical velocity in the downhill slope tunnel is greater than in the horizontal tunnel. Ballesteros *et al.* (2006) numerically studied the effect of tunnel slope on the ventilation semi-transversal system. The number of exhaustion openings should be increased in the ascending direction to exhaust more smoke. Lin *et al.* (2019) studied the fire behaviors, induced longitudinal ventilation caused by stack effect, temperature distribution in a naturally inclined tunnel. Su *et al.* (2023) investigated the effect of the critical velocity, confinement velocity, and smoke backlayering length in the case of an underground train with door-opening scenarios in a tunnel fire.

The longitudinal temperature rise is a key parameter to evaluate the lining failure and smoke backflow distance in the tunnel. Under natural ventilation, the chimney effect in an inclined tunnel would result in an asymmetrical symmetric temperature distribution between the two fire sources on both sides. Hu *et al.* (2013) found that the previous model overestimates the ceiling maximum temperature in inclined tunnels and that the longitudinal temperature decays faster with a higher slope. The one-direction flow of smoke (uphill) would be achieved with the increasing tunnel slope under natural ventilation (Wan *et al*., 2019). Under these circumstances, the excess temperature rises downhill and can be neglected. Oka *et al*. (2013) considered an inclination angle of 20° to study the temperature property in a rectangular inclined tunnel. They found that the dependence of temperature attenuation against distance in the upward direction increased with the greater inclination angle. Huo *et al*. (2015) found that the previous empirical model for ceiling excess temperature is not applicable to predict the temperature rise in an inclined tunnel with a bounded wall. They modified the previous empirical model to an application for the rectangular inclined tunnel with a titled angle varied from 0° to 30°. Due to the tunnel cross-section affecting heat losses, the longitudinal temperature distribution was varied with different cross-sections of inclined tunnels (Zhao *et al*., 2019). For the rectangular inclined tunnel with different widths, Wang *et al*. (2020) proposed the aspect ratio of tunnel width to height to correlate the longitudinal temperature. Yang *et al*. (2021) proposed a dimensionless model to predict the temperature longitudinal decay over both uphill and downhill in a circular inclined tunnel. Based on the full-scale curved tunnel fire experiments, Zhong *et al*. (2016) investigated the variation of the vertical position of the maximum temperature along the inclined tunnel and smoke backflow length. The maximum temperature would have occurred at the uphill region but not right above the fire source in the inclined tunnel (Ji *et al*. 2015). Gao *et al*. (2022) also studied the vertical temperature distribution in an inclined tunnel with the titled angle from 0° to 15°, and an empirical model for the maximum temperature was proposed. After investigating the temperature property along an inclined curved tunnel, Yu *et al*. (2018) suggested that increasing the number of exhaust vents and supplying air from downstream can optimise smoke exhaustion. Tao *et al*. (2020) experimentally studied the smoke control and maximum temperature in an inclined tunnel under semi-transverse ventilation. The inclined tunnel was always blocked by vehicles. Under these circumstances, the smoke flow is affected by the coupling of blockage and chimney effect that results in the different temperature attenuations along the tunnel. Han *et al*. (2021) revealed the coupling effect of blockage and tunnel slope on temperature longitudinal decay to modify the previous model.

The temperature distribution upstream depends on the smoke backflow distance, which can be determined using upstream sharp temperature decrease (Ji *et al*., 2015). Kume *et al*. (2020) carried out experiments to study the smoke front flow behaviour and revealed the smoke backlayering length in the inclined tunnel. The smoke flow length in the uphill direction would be enhanced by the stack effect. Yang *et al*. (2018) studied the smoke backlayering length in a naturally sloping tunnel based on the brine water experiment and quantified the smoke backlayering length. The driving force to prevent the smoke backflow in the downhill tunnel not only resists static pressure difference but the stack effect. Du *et al*. (2018) argued that the driving force to control smoke backflow was remarkably larger than that in a horizontal tunnel due to the stack effect. This critical driving force for preventing smoke backflow in inclined tunnels has been revealed by Li and Yang (2020a). Yi *et al*. (2014) found that the critical velocity (no smoke backflow) in an inclined tunnel was different from that in a horizontal tunnel. Weng *et al*. (2016) dimensionless analyzed the critical velocity in an inclined tunnel and proposed a dimensionless correlation to qualify the critical velocity for an inclined tunnel. Jiang and Xiao (2022) suggested that the critical velocity in an inclined tunnel should be considered based on the buoyant plume driven by buoyance or momentum. The influence of tunnel slope on the critical velocity is small under a momentum-driven plume, but that influence is large under a buoyance-driven plume. Jiang *et al*. (2021) considered the stack competitive effect between the fire source's two sides in a V-shaped slope tunnel. The air inflow is induced by the stack effect in a sloped tunnel, which is dominated by the fire size and inclination angle (Zhao *et al*., 2019), thus, that brings difficult to determine the critical velocity.

In practice, the rapid construction of branched tunnels as a result of urbanization has led to the widespread use of tunnels with multiple inclinations, such as the Urban Traffic Link Tunnel. However, conventional models for single-point inclined tunnels are not sufficient for predicting smoke propagation in inclined bifurcated tunnels. Previous models for ordinary inclined tunnels without bifurcations have been unable to accurately predict the smoke backlayering length and critical velocity in these complex environments. Chen *et al*. (2020) and Lei *et al*. (2022) studied the influence of ramp slope on Y-shaped bifurcation tunnel and T-shaped bifurcation tunnel. They argued that the proportion of mass flux in branches was affected by the sloped bifurcation tunnel. That means that the ventilation velocity to prevent smoke in a branched tunnel is different from an ordinary tunnel. Huang *et al*. (2020) proposed an empirical model to predict critical velocity in a branched tunnel, but not considering the tunnel slope. Li and Yang (2020b) investigated the driving force for preventing smoke in a branched tunnel with an inclined ramp. Li *et al*., (2023) have found that the maximum exceedance temperature in tunnels increases as the ramp slope decreases due to the stack effect enhancing the entrainment of air and accelerating the smoke flow.

However, the characteristics of smoke movement in inclined tunnels with bifurcations has been relatively understudied. In particular, the effects of the stack effect on the induced air inflow velocity and its interactions with the diverging flow and local resistance have not been thoroughly investigated. The length of smoke backlayering has not been analyzed on the current model for branched tunnels with inclined mainlines. Thus, it is urgent to study the smoke backflow behavior and clarify the smoke backlayering length in this branched tunnel with an inclined mainline.

This research aims to develop a simple model to quantitatively determine the length of smoke backlayering in a branched tunnel with an inclined downstream mainline. Numerical simulations were carried out to obtain the smoke backlayering length and induced airflow velocity under different mainline tunnel slopes and heat-release rates. Additionally, a method for predicting the airflow velocity induced by the stack effect was developed. The numerical results and theoretical analysis were used to establish a mathematical model for the smoke backlayering length in a branched tunnel with inclined downstream. The predicted model was then compared with the numerical results.

2. Numerical modelling

2.1 The physical model

The Fire Dynamics Simulator (FDS) code was employed to simulate the tunnel fire, which has been fully verified (Wan *et al*., 2019; Wang *et al*., 2020). FDS is a practical computational fluid dynamics (CFD) model of fire-driven fluid flow developed by NIST (the U.S. National Institute of Standards and Technology). FDS numerically solves a form of the Navier-Stokes equation appropriate for low-speed (Ma < 0.3), thermally-driven flow with an emphasis on smoke and heat transport from fires. The large edgy simulation, which disposes of turbulence and buoyancy well, was carried out to calculate the smoke movement and heat flow.

1/20 small-scale experimental results in a previous study were used to validate the accuracy of FDS for bifurcation tunnel fire (Huang *et al*., 2021). The scale bifurcation tunnel is 0.355m in height, the mainline tunnel before shunting was 19m in length with 0.675m width (including 4.0m extension region), the mainline tunnel after shunting was 10.86m in length with 0.487m width, and the ramp was 9.23m length with 0.375m width. Small-scale experiments with heat release rates of 1.72 kW, 3.45 kW and 5.18 kW were carried out under natural ventilation. The numerical modelling was full-scale. The small-scale experimental results were transferred to full-scale value by Froude law. The temperature at ramp entry was used to compare with numerical modelling. The temperature obtained by numerical modelling agrees well with the experimental results under a quasi-steady state, as shown in Fig.1. Thus, it is reliable using FDS to simulate the smoke movement in a branched tunnel.

The full scale common urban branched tunnel is constructed by three parts which are mainline tunnel before shunting, mainline tunnel after shunting and ramp. The detail dimension shows in Fig.2. The mainline tunnel before shunting is 230m long, 13.5m width and 7m high. The mainline tunnel after shunting is 150m long, 9.7m width and 7m high. The dimension of ramp is 150m length with 7m width and 7m height. Three branched angles 5°, 15° and 30° were considered in present study. According to the *Code for design of urban underground road engineering* (CJJ221-2015), the maximum longitudinal tunnel slope of underground road tunnel should not exceed 8%, the tunnel slope in American and Norway is not exceeding 4% and 7%, respectively. Thus, eight positive tunnel slope of mainline tunnel before shunting varied from 0% to 7% with interval 1% were considered.

The fire source with dimension 1m×2m was located at the joint node region 150m away from the right end of the horizontal mainline tunnel. The fire source fuel was set as N-heptane, and the heat release rates were 3MW, 5MW, 10MW, 15MW and 20MW, which represented the car, bus, and lorry fires (Ji *et al.*, 2018). The material tunnel wall was set as concrete with its thermal properties (density is 2280.0 kg/m^3, specific heat is 1.04 kJ/ (kg K), conductivity is 1.8 W/ (m K), emissivity is 0.9, the absorption coefficient is 50,000 l/m) (Wang *et al.*, 2020). The ambient temperature was 293K, the relative humidity was 40%, and the ambient temperature was set as 101325 Pa. The three ends of the branched tunnel were set to be open. The test cases are listed in Table 1. The first group presents a series of conditions with a bifurcation angle of 5° but a different tunnel slope (0-7%). To better distinguish the influence of the bifurcation angle on smoke backflow in a sloped tunnel, another group with three bifurcation angles 5°, 15° and 30° with a tunnel slope of 5% is established.

The thermocouples were used to measure the temperature along the mainline tunnel and ramp centerline. The thermocouple tree was installed near the fire source on two sides 50m to measure the horizontal and vertical temperature. The interval of the thermocouple tree was 2m. There were six thermocouples in each tree with a vertical interval distance of 1m, and the highest one was below a tunnel ceiling of 0.1m. Away from the fire source 50m, the thermocouple was placed 0.1m underneath the ceiling along the longitudinal direction with an interval of 4m. The flow velocity and the pressure in the tunnel were also measured. The time average value under the quasi-steady state was used in the following analysis.

Table 1 Test cases.

Description	No.	HRR (MW)	Branched angle (°)	Mainline tunnel slope (%)
Tunnel slope changed	1-40	3, 5, 10, 15, 20	5	0, 1, 2, 3, 4, 5, 6, 7
Bifurcation angle changed	41-50	3, 5, 10, 15, 20	15, 30	5

2.2 The mesh size

The mesh size is an important factor, which affects the accuracy of results and computation time in FDS simulation. The mesh size is related to the characteristic fire diameter D^*, where the non-dimension expression (D^*/δ_x) can be used to determine the mesh size. The characteristic diameter can be expressed as following:

$$D^* = \left(\frac{Q}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \tag{1}$$

The previous study suggested that the $\delta_x = 0.1D^*$ could obtain viable results (Tilley *et al.*, 2012). The D^* for the least heat-release rate in this study of 5MW is 1.8m. To save computation time and produce sufficient accuracy results, five mesh sizes between $0.1D^*$ two sides were adopted to analyze the independence, which was 0.5m, 0.4m, 0.3m 0.2m and 0.1m. The mesh independence analysis was conducted in a branched tunnel with a bifurcation angle of 5° of this study. The heat release rate of fire source 5MW was selected and placed in a joint node, the mainline tunnel slope was 3° . The longitudinal temperature along the mainline tunnel centerline was selected as a criterion for sensitivity analysis, as shown in Fig.3. We observe that the numerical result is independent of the mesh size at less than 0.3m. Under this circumstance, the corresponding proportion of D^*/δ_x is 6. Thus, to save computational resources and output accurate results, the multi-domain mesh was conducted. The proportion of $D^*/\delta_x = 6$ was adopted to determine the mesh size between the fire source two sides 50m, the mesh side in other regions doubled.

3 Analytical modelling

The smoke movement is driven by initial momentum due to combustion heat. The thermal buoyancy induced by the stack effect and the hydrostatic pressure would affect the smoke spread in the inclined tunnel with bifurcation. The bifurcation structure would influence the local resistance and turbulent the airflow. Fig. 4 shows the schematic of smoke movement in a branched tunnel with positive mainline inclination. The smoke plume tilted to the upper tunnel ends due to the density difference caused by the stack effect. The influence of the stack effect on the smoke plume can be deemed as a virtual longitudinal ventilation from the lower entrance to the upper ends (Kong *et al*., 2021). If the stack effect is relatively strong, which means the virtual longitudinal ventilation is compared with smoke layer momentum, the smoke would not exhaust through the lower entrance and the smoke backlayering upstream occurred. Additionally, the virtual longitudinal ventilation reaches a critical value to prevent smoke backflow under the stronger stack effect. Under this circumstance, there is no smoke backflow upstream that is conducive to smoke control and evacuation.

The stack effect in a sloped tunnel can be expressed as Eq. (2), where the virtual ventilation velocity V' is proposed to evaluate the kinetic energy caused by the stack effect.

$$P_{stack,d} = \int_0^L \left(\rho_\infty - \rho_s\right) g \sin\beta dx = \frac{1}{2}\rho_\infty V'^2, \sin\beta = \frac{h}{\sqrt{l^2 + h^2}} \tag{2}$$

where $P_{stack,d}$ is the stack pressure in Pa.

Based on the ideal gas law, the density difference can be expressed by temperature rise as $\rho_\infty/\rho_s = T/T_\infty$. Eq. (1) can be transferred as

$$P_{stack,d} = \int_0^L \rho_\infty \left(\frac{\Delta T}{T}\right) g \sin\beta dx = \frac{1}{2}\rho_\infty V'^2 \tag{3}$$

The smoke plume spreads in the vertical direction and impinges on the inclined tunnel ceiling, then spread along the tunnel ceiling, as shown in Fig. 5. The smoke movement in the mainline tunnel upstream of the fire source and the ramp can be seen as a horizontal tunnel. However, the smoke spreads in the downstream inclined tunnel that caused the virtual airflow velocity V' along the tunnel. Thus, the smoke movement in the vertical region can be seen as a bending plume induced by ventilation. The cross-section of the vertical plume is assumed to be circular with a radius *of* r, and the velocity and temperature profiles are top hat. The Boussinesq approximation is valid. The chemical reaction and variations in molecular weight and specific heat are ignored (Alpert, 1975). The governing equations of mass are expressed as follows.

$$\frac{d}{ds}(\pi r^2 v \rho_s) = 2\pi r \delta (v - V' \cos\alpha)\rho_\infty + 2\pi r \eta V' \sin\alpha \rho_\infty \tag{4}$$

The conservation of momentum in the vertical direction equals the buoyancy force induced by the density difference. From the basic equation of the ideal plume $\triangle \rho r^2 = Q/\pi v c_p T_\infty$, the momentum equation in the vertical direction can be expressed as Eq. (5).

$$\frac{d}{dz}(\pi r^2 \rho_s v^2 \sin\alpha) = Qg/vc_p T_\infty \tag{5}$$

The dimension relationship between the trajectory of plume and axis can be expressed as Eq. (6).

$$\frac{dz}{ds} = \sin\alpha, \frac{dx}{ds} = \cos\alpha \tag{6}$$

It is assumed that the radius of the plume, and the velocity in the vertical direction change as some power of height, expressed as Eq. (7).

$$\begin{cases} r = C_1 z^m \\ v \sin\alpha = C_2 z^n \end{cases} \tag{7}$$

where C_1 and C_2 are constants, m and n are power coefficients.

Submitted Eq. (6) and (7) into Eq. (4) and (5), then the conversation equation of mass is divided by sinα. The following Eq. (8), the conservation equation of mass and momentum is given as follows.

$$\begin{cases} \frac{d}{dz}(\pi \rho_s C_1^2 C_2 z^{2m+n}) = \frac{2\pi\delta\rho_\infty}{\sin\alpha} C_1 C_2 z^{m+n} + 2\pi\eta\rho_\infty C_1 z^m V' - \frac{2\pi\delta\rho_\infty}{\sin\alpha} C_1 z^m V' \cos\alpha \\ \frac{d}{dz}(\frac{1}{\sin^2\alpha} \pi \rho_s C_1^2 C_2^2 z^{2m+2n}) = \frac{\dot{Q} g}{c_p T_\infty C_2} z^{-n} \end{cases} \tag{8}$$

The power of z must be the same on both sides of the above equation. Similarly, the constants for the same power of z must result in identical on both sides of Eq. (8). Therefore, the entrainment coefficient $\eta = \delta \cot\alpha$ is obtained. Differentiate and Simplified the Eq. (8), the following function can be given

$$\begin{cases} r = \frac{6\delta}{5\sin\alpha} z \\ v = \left(\frac{25\sin\alpha}{48\delta^2} \frac{g}{\pi c_p T_\infty \rho_\infty} \right)^{1/3} \cdot Q^{1/3} \cdot z^{-1/3} \end{cases} \tag{9}$$

The plume angle α is influenced by the virtual wind caused by the stack effect. The plume axis velocity is controlled by vertical velocity without wind-blown and longitudinal wind velocity. The virtual wind velocity is mainly dependent on the fire size and the elevation difference between the lower and upper ends of the tunnel. Previous studies (Li *et al*., 2010; Du *et* al., 2020, 2022), have shown that the virtual velocity can be normalized using the buoyancy flux parameter $(Qg/C_pT_\infty\rho_\infty H)^{1/3}$. The elevation difference between the two ends of the inclined tunnel can be determined using $L\sin\beta$ (Fan *et al.* 2017). Therefore, the dimensionless expression for the virtual wind velocity can be given as follows:

$$V'^{*}=V'\Bigg/\left(\frac{Qg}{c_pT_\infty\rho_\infty H}\right)^{1/3}\propto\frac{L\sin\beta}{H} \tag{10}$$

The sine of flame angle α is a function of dimensionless virtual velocity, which can reference the plume angle of wind blow pool fire (Quintiere *et al.*, 1981), given as

$$\sin\alpha=\begin{cases}1, & V'^{*}\le 0.19\\ \left(5.26V'^{*}\right)^{-1/2}, & V'^{*}>0.19\end{cases} \tag{11}$$

The plume velocity beneath the inclined tunnel ceiling can be expressed as

$$v=\left(\frac{25\sin\alpha}{48\delta^2}\frac{g}{\pi c_pT_\infty\rho_\infty}\right)^{1/3}\cdot Q^{1/3}\cdot(H\sin\beta)^{-1/3} \tag{12}$$

The kinetic energy of the plume breaks down into three parts after impinging the tunnel ceiling, which includes the kinetic energy of smoke flow in the same direction and opposite direction of the static effect force, the other part is transferred as thermal energy due to friction. Thus, after impingement, the smoke flow velocity near the tunnel ceiling is proportional to the vertical velocity beneath the tunnel ceiling. The fire source is located at a joint node region in the present study. One part of the smoke content would be too diverse to ramp. Thus, it is assumed that the hot smoke in the mainline at both sides of the fire source was produced by effective heat release rate Q_m. The smoke flow velocity adjacent to the ceiling impingement point is the maximum value (Alpert, 1975; Zhang, 1997), it is given as

$$u_{up,\max}=C_3\left(\frac{25\sin\alpha}{48\delta^2}\frac{g}{\pi c_pT_\infty\rho_\infty}\right)^{1/3}\cdot {Q_m}^{1/3}\cdot(H\sin\beta)^{-1/3} \tag{13}$$

where $u_{up,max}$ is the maximum smoke flow velocity in the opposite stack effect direction after impingement in m/s, C_3 is the coefficient, Q_m is effectively heat release rate in the mainline at both sides of the fire source, $Q_m=C_4Q$, C_4 is a coefficient less than 1.

The smoke movement upstream of the fire (horizontal region) is opposite to the virtual wind. Under low wind velocity, $1/2\rho_s u^2_{up,max}>1/2\rho V'^2$, the phenomenon of backlayering occurs. The energy of smoke backlayering is gradually consumed by friction force and hydrostatic pressure of airflow (Huang *et al*., 2022). Based on the conservation of energy, the following Eq (14) can be given. The mass flow equation is given as $\rho u_{up} = \rho_j u_{up,max}$ (Zhang, 1997).

$$\rho_j C_3 \left(\frac{25\sin\alpha}{48\delta^2} \frac{g}{\pi c_p T_\infty \rho_\infty} \right)^{1/3} \cdot Q_m^{\ 1/3} \cdot (H\sin\beta)^{-1/3} du_{up} = -\left(\frac{\lambda}{2d}\rho_a V'^2 + \frac{\lambda}{2d_s}\rho_j C_3 \left(\frac{25\sin\alpha}{48\delta^2} \frac{g}{\pi c_p T_\infty \rho_\infty} \right)^{1/3} \cdot Q_m^{\ 1/3} \cdot (H\sin\beta)^{-1/3} u_{up}\right) dx \tag{14}$$

where ρ_j is the smoke density beginning reverse flow in kg/m^3, λ is the friction coefficient, and d and d_s are the hydraulic diameter of the tunnel and reverse smoke layer in m, respectively.

Based on the boundary condition of u_{up}=$u_{up,max}$ during x=0, Solving the integral Eq.(14) gives the smoke reverse flow velocity along the tunnel.

$$u_{up} = u_{up,\max} e^{(-\frac{\lambda}{2d_s}x)} - \frac{\rho_\infty V'^2}{\rho_j C_3 \frac{d}{d_s} \left(\frac{25\sin\alpha}{48\delta^2} \frac{g}{\pi c_p T_\infty \rho_\infty} \right)^{1/3} \cdot Q_m^{\ 1/3} \cdot (H\sin\beta)^{-1/3}} \left(1 - e^{(-\frac{\lambda}{2d_s}x)}\right) \tag{15}$$

Based on the ideal gas law, the density relationship between fresh air and smoke can be expressed using the temperature rise, $\rho_\infty/\rho_j = T_{max}/T_\infty$. The backlayering of smoke stagnates during u_{up}=0. The distance from the stagnation point to the fire source is the smoke backlayering length. Based on L=x during u_{up}=0, the smoke backlayering length can be obtained by solving Eq. (15), given as

$$L = \frac{2d_s}{\lambda} \ln\left(1 + C\frac{T_a}{T_j} \frac{\left(\frac{25\sin\alpha}{48\delta^2} \frac{g}{\pi c_p T_\infty \rho_\infty} \right)^{2/3} \cdot Q_m^{\ 2/3} \cdot (H\sin\beta)^{-2/3}}{V'^2} \right) \tag{16}$$

The hydraulic diameter of the smoke layer is controlled by the smoke with the fire size and wind velocity (He *et al*., 2021; Mei *et al*., 2017). The tunnel width and the friction coefficient are constant for a given tunnel structure. Thus, Eq. (16) can be further simplified as

$$L = a\ln\left(b + U\frac{T_a}{T_j} \left(\frac{25\sin\alpha}{48\delta^2 \sin\beta} \frac{Qg}{\pi H c_p T_\infty \rho_\infty} \right)^{2/3} V'^{-2} \right) \tag{17}$$

where a, b and U are the coefficients. The maximum smoke temperature T_j beneath the tunnel ceiling was studied in our previous work reference (Huang *et al*., 2019).

4. Results and discussion

4.1 Smoke movement in inclined mainline tunnel

The typical velocity profile along the centerline of the mainline tunnel with a bifurcation angle of 5° is shown in Fig. 6. In the horizontal region, the velocity direction beneath the ceiling is towards the entrance due to the dominance of the buoyancy force on smoke movement. However, the velocity direction in the lower air layer leans towards to fire source due to the air entrainment. The velocity profile gradually inclined to the upper portal of the mainline with the increasing tunnel slope. The entrainment mechanism of combustion in a bifurcation tunnel and the stack effect contribute to this inclined velocity profile. The cross-section space of the tunnel between the joint node on the two sides is not uniform. The fire source in the present work was located at a joint node, thus, the air entrainment is asymmetrical at two sides. The cross-section space at the horizontal ends (ramp and mainline) is larger than another side, more fresh air is entrained into the fire source through this section's lower layer. The fresh air layer at the upper side of the mainline was thinner and had less air entrainment into the fire plume. However, the smoke layer is a little tilted to the ramp direction near the fire source also due to the relatively large cross-section area in this direction. Thus, the curved vertical fire plume occurs in a horizontal tunnel, and the vortex in the direction after shunting is more obvious. This asymmetrical air entrainment at the fire source on two sides results in a smoke plume slightly inclined, which can be seen from the longitudinal velocity profile in the horizontal tunnel. This consists of a previous experimental study (Huang *et al*., 2019). Under the circumstance, no stack effect exists in horizontal smoke movement, only the asymmetrical entrainment induced the inclined flow. The inclination of smoke movement due to the asymmetrical entrainment is limited, as shown in Fig.6 (a).

In the tilted tunnel, the velocity profile tends to the upper portal direction more significantly than that in the horizontal one. And the inclined degree in the vicinity of the fire source increased with the mainline slope, as well the velocity profile gradually filled up the tunnel cross-section. Under this circumstance, the stack effect dominates the smoke-inclined flow (Gao *et al*., 2022). Under a mainline slope of 3%, caused backflow velocity beneath the ceiling because of the backlayering of smoke. The velocity profile from the fire source to the upper ends filled the downstream because of the heat smoke layer dominated by the stack effect. When the tunnel slope was 5% or 7%, only the unidirectional velocity occurred at the horizontally upstream region. That indicates that the smoke backflow has been prevented due to a relatively strong stack effect. For a given tunnel trajectory length, the elevation difference between the fire source and upper end increased with the larger tunnel slope which results in the stronger pressure difference $P=\triangle\rho gLsin\beta$. Thus, the smoke layer backward flow upstream of the fire source fades away. Simultaneously, the entrainment flow at the downstream lower air layer disappeared gradually and was filled with a smoke layer with a 5% and 7% tunnel slope. This indicates that the longitudinal wind in the tunnel has been induced by the stack effect and that the wind velocity increases with a steeper tunnel slope. This induced longitudinal wind can effectively confine the smoke backflow. The smoke backlayering is shown to be confined to the upstream outlet by the induced wind for tunnel slopes greater than 3%.

Fig.7 shows the airflow velocity in the tunnel, the smoke movement velocity in the branched tunnel with a tilted mainline is also sensitive to heat release rate and bifurcation angle. For a given inclination of the mainline, the longitudinal velocity increased with the increasing heat release rate shown in Fig.7 (a). For a given heat release rate, the greater longitudinal wind velocity at the upstream horizontal region results from a larger tunnel slope, and the induced longitudinal wind velocity increases slightly with the increasing bifurcation angle, as shown in Fig7 (b). The main reason is that the open area along the longitudinal direction decreased upstream with the larger bifurcation angle. Due to the flow direction change and relatively more smoke entry to the uphill region to enhance the buoyance force, driving smoke flow under a larger bifurcation angle. However, the entrainment air from the ramp entrance to the fire source must overcome greater local resistance and kinetic energy consumption, thus, more fresh air is entrained from the mainline horizontal end to balance pressure and combustion.

Fig.8 presents the dimensionless expression of virtual wind velocity varied with the sine of tunnel inclination and sine of bifurcation angle. Under a bifurcation angle of 5° , the dimensionless value of virtual wind velocity is defined as reference one ($V_{ref}^{'*}$) that keeps consistent for a given tunnel slope. The dimensionless parameter of virtual velocity can be well normalized using $L\mathrm{sin}\beta/H$, and the virtual velocity is given by Eq. (18). The larger bifurcation angle results in a higher virtual wind velocity, which increases linearly with $\mathrm{sin}\theta$. The dimensionless parameter of virtual velocity under varied bifurcation angles ($V^{'*}$) are as a numerator and $V_{ref}^{'*}$ as a denominator. The ratio of the dimensionless parameters against the sine of the bifurcation angle influence is shown in Fig. (8). Thus, the relationship between virtual wind velocity, tunnel slope and bifurcation angle is given by Eq. (19).

$$V'_{\theta=5^{\circ}}=0.3\left(\frac{Qg}{c_p T_{\infty}\rho_{\infty}H}\right)^{1/3}\left(\frac{L\sin\beta}{H}\right)^{2/5} \tag{18}$$

$$V'=0.14\left(\frac{Qg}{c_p T_{\infty}\rho_{\infty}H}\right)^{1/3}\left(\frac{L\sin\beta}{H}\right)^{2/5}(0.96+0.43\sin\theta) \tag{19}$$

4.2 Smoke backlayering length in slope tunnel

For the inclination of the mainline less than 3%, the smoke exhausts through the mainline two sides. With increasing the tunnel slope, the smoke stagnates in the horizontal region due to the stack effect. The smoke backlayering length decreased with the increasing tunnel slope (Wan *et al.*, 2019), as shown in Fig. 9. For a given tunnel slope, the smoke backlayering length decreased slightly with the increasing heat release rate during tunnel slope greater than 4%. The aforementioned results are due to the stack effect on the upper end and the relative dominance of the horizontal initial force at the horizontal region portal. Under the circumstance, the height difference between the fire source and the upper end is relatively high, the stack effect increased faster compared with the horizontal initial force under a stronger heat release rate. That the stack effect dominates the smoke movement to the upper end, and the effect of heat release rate on smoke backflow distance cannot be neglected during the tunnel slope greater than 4%. However, the previous study by Zhang *et al.* (2021). claimed that the heat release rate has no significant effect on smoke backlayering length under large inclination or tunnel length. Additionally, Oka (*et al.*, 2013) suggested that the smoke-backlayering length increases with the heat release rate and is proportional to $Q^{2/5}$ under natural ventilation. The reason may be that the difference in tunnel structure and elevation difference ss the previous study was conducted in a single point downhill tunnel but this tunnel is a branched one constructed with an inclined mainline region, horizontal mainline region and ramp. In a previous study, the downhill was also inclined to enhance the stack effect and resistance losses of backlayering.

For the heat release rate increased to 20MW, the smoke backflow was contained in 4*H* under a tunnel slope of 7%. That indicates that the enhancement effect of the heat release rate on the stack effect is sufficient to control smoke backflow, which is favourable for pedestrian evacuation upstream. With an increasing heat release rate, the virtual wind blow velocity induced by the stake effect was to the confinement velocity to prevent the smoke backflow under a tunnel slope of 7%.

For the tunnel slope of 5%, the bifurcation angle increased from 5° to 30° , and the smoke-backlayering length is shorter and this difference increased with the firepower. The smoke will be radial spread after impinging on the tunnel ceiling, while the initial force pushing one part of the smoke enters the ramp. With the increasing bifurcation angle, the included angle of initial force in the ramp and mainline tunnel increases, and the effective cross-section in the ramp for air entrainment parallel to the mainline tunnel decreases. Thus, more air is entrained from the horizontal mainline tunnel portal to balance the pressure difference induced by the stack effect. Under this circumstance, the virtual wind flow in mainline tunnels decreases. The smoke backlayering length decreased under a larger bifurcation angle.

The smoke backlayering length in the branched tunnel is compared with the predictions by the previous empirical model under natural ventilation (Wan *et al*., 2019; Oka *et al*., 2013; Zhang *et al*., 2021; Kong *et al*., 2021), as shown in Fig.10. It can be seen from Fig.10 That the previous model proposed by Wan *et al*. (2019) and Zhang *et al.* (2021) underestimates the smoke backlayering length in a branched tunnel. The empirical model of smoke backlayering length established by Wan *et al*. (2019) is based on natural tunnel fires with a vertical shaft. The smoke is exhausted through the uphill shaft, which means a less inclined length is downstream, thus, the stack effect in the inclined region weakens. However, the vertical shaft enhances the stack effect due to an increase in the height difference. The cooperation mechanical or weaken the effect as reduced inclined length and the enhancement effect of vertical height is not applied to this condition. Oka *et al.* (2013) and Kong *et al.* (2021) considered the effect of the heat release rate on smoke backlayering length, while the smoke backlayering length was overestimated in present conditions. Thus, the previous empirical expression for smoke backlayering length under natural ventilation applies to a branched tunnel with a tilted mainline. Therefore, it is urgent to develop a new general correlation for the smoke backlayering length in branched tunnels with different mainline tunnel slopes.

The non-dimension smoke backlayering lengths L/H are correlated using $T_a/T_j\,(25\sin\alpha/48\delta^2\sin\beta)^{2/3}/V'^{*2}$, as shown in Fig.11. The L/H is logarithmically related to the dimensionless parameters including the tunnel slope, bifurcation angle, heat release rate, virtual wind velocity and maximum temperature beneath the tunnel ceiling. The correlation L/H is given as

$$\frac{L}{H}=2.7\ln\left(\frac{T_a}{T_j}\left(\frac{25\sin\alpha}{48\delta^2\sin\beta}\frac{Qg}{c_pT_\infty\rho_\infty H}\right)^{2/3}V'^{-2}-116\right) \tag{20}$$

The smoke backlayering lengths calculated using Eq. (20) are compared with the numerical results. Fig.12 Shows the smoke backlayering length can be well calculated using Eq. (20). The present mode applies to a branched tunnel with an inclined downstream mainline region combined with a horizontally upstream region. For the branched tunnel with a whole tilted mainline, the buoyance force tilted upstream would be enhanced and the smoke reverse flow distance would be weakened, which will be studied in future work.

5 Conclusions

The present paper numerically investigates the smoke movement characteristics in branched tunnel with inclined downstream mainline, the virtual wind velocity in horizontal region induced by stack effect and the smoke backlayering length is specifically focused. The empirical model for predicting the virtual wind velocity and smoke backlayering length was developed taking the tunnel slope, bifurcation angle into consideration. The major conclusions are as follows:

(1) It is demonstrated that in a branched tunnel with an inclined downstream mainline and a horizontal upstream, the induced airflow velocity may not be sufficient to prevent smoke from exhausting through the horizontal entrance for mainline inclinations of less than 3%. In this case, the opposite flow velocity is observed at the horizontal region with a lower inclination of the mainline. The inflow velocity from lower entrance to the upper end is unidirectional with the tunnel slope equal to or larger than 5%.

(2) The study shows that the flow velocity along the mainline is significantly influenced by the tunnel slope. Higher induced wind velocities are observed under a steeper mainline tunnel slope. The wind velocity is also strengthened by a larger heat-release rate due to the buoyancy force enhancing the stack effect. The effect of the bifurcation angle on induced wind velocity is limited and can be accurately predicted using the sine of the bifurcation angle. A global model for induced airflow velocity is developed by considering the inclination of the tunnel, tunnel length, heat-release rate, and bifurcation angle.

(3) The paper presents evidence that the smoke-backlayering length is shorter with a higher difference between the fire source and the upper end of the mainline. The smoke backflow distance is also reduced under larger bifurcation angles and

stronger fires, as more smoke is pushed to the uphill region with a stronger buoyancy force. A new non-dimensional predicted model for smoke backlayering length in a branched tunnel with a tilted mainline is proposed and shown to agree reasonably well with the numerical results. This model takes into account the effects of tunnel slope, bifurcation angle, and heat-release rate on smoke backflow distance.

This study provides a simple and effective model for predicting the smoke backlayering length in a branched tunnel with an inclined downstream mainline. One potential limitation of the study is that it only considers a fire located at joint node and does not account for the potential effects of fire position or the interaction between multiple fires in the branched tunnel with inclined mainline. Further research could focus on extending the proposed model to include the effects of fire locations and different fire scenarios on the smoke backlayering length in a branched tunnel with inclined mainline. Additionally, further studies could consider the effects of ventilation systems on the smoke backlayering length, as well as the potential use of the proposed model for fire safety design and emergency response planning in branched tunnels.

CRediT authorship contribution statement

Youbo Huang: Funding acquisition, Conceptualisation, Formal analysis, Methodology, Writing - original draft. **Xi Liu**: Data curation, Writing - original draft, Writing - review & editing. **Bingyan Dong**: Investigation, Writing - review, & editing. **Hua Zhong**: Writing - review & editing, Methodology. **Bin Wang**: Data curation, Writing - review & editing. **Qiwei Dong**: Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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List of figures

List of table