# Effect of inclined mainline on smoke back-layering length in a naturally branched tunnel fire

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**Abstract**

The effect of mainline tunnel slope and bifurcation angle on smoke movement characteristics and smoke backflow distance in branched tunnel with tilted downstream mainline were investigated theoretically and numerically in present paper. The downstream mainline tunnel slope varied from 0% to 7% with interval 1% was carried out under different fire sizes (3MW, 5MW, 10MW, 15MW, 20MW) and bifurcation angles (5°, 10°, 15°). A predicted model to calculate the virtual wind velocity induced by stack effect and smoke back-layering length in mainline tunnel was proposed based on the theoretical analysis. Results show that the mainline tunnel slope from fire source to upper end has significant effect on longitudinal velocity distribution induced by stack effect. The virtual wind velocity in horizontal mainline region are proposed which increased with larger tunnel slope and stronger fire size. The effect of bifurcation angle on virtual wind velocity induced by stack effect is limited, but could not neglected under relatively large heat release rate. The dimensionless velocity is well normalized using sine tunnel slope and bifurcation angle. With the larger downstream mainline tunnel slope, the longitudinal temperature in upstream horizontal mainline region decreased faster due to the shorter smoke backflow. The stronger heat release rate slightly reduced the smoke back-layering length, but the higher mainline tunnel slope greatly controlled the smoke into the upstream mainline region. The established model for smoke back-layering length in branched tunnel with tilted downstream mainline takes the tunnel slope, bifurcation angle and heat release rate into consideration, that shows the dimensionless smoke back-layering length is logarithmically related to proposed dimensionless parameter. The predicted value of smoke back-layering length is in good agreement with simulated results.

**Keywords**: branched tunnel, tunnel slope, back-layering length, bifurcation angle, natural ventilation

## 1. Introduction

Nowadays, the tunnel fire accidents have been occurred and result 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 injured in 2014. The accumulation and propagation of smoke in tunnel a long-narrow confined space is one mainly threaten for personal evacuation. Recently, with the development of urban underground transportation, the branched tunnel with multiple portals was extensively constructed. The smoke propagation in this tunnel would be more complex compared with ordinary single-point tunnel. The branched tunnel always has multiple inclinations in practical engineering which would form chimney effect to promote smoke movement in uphill. The smoke back-layering length and critical velocity to prevent smoke backflow would be varied in sloped bifurcation tunnel. It is urgently to study the smoke backflow behavior and clarified the smoke back-layering length in sloped bifurcation tunnel.

Many previous studies about tunnel fire has been focused on the smoke propagation in inclined tunnel. Atkinson and Wu (1996) claimed that the critical velocity in downhill slop tunnel is greater than in horizontal tunnel. Tajadura *et al*. (2006) numerically studied the effect of tunnel slope on ventilation semi-transversal system. It is suggested that the number of exhaustion opening should be increased in ascending direction to exhaust more smoke. Merci (2008) studied the global chimney effect induced by a fire in a sloped tunnel, and one-dimensional global model were proposed based on considering multiple factors.

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

The temperature distribution at upstream dependents on the smoke backflow distance another key parameter which can be determined using upstream sharp temperature decrease (Ji *et al*., 2015). Kume *et al*. (2020) carried out experiments to studied the smoke front flow behavior in inclined tunnel, and revealed the smoke length under different airflow velocity. The smoke flow length in uphill direction would be enhanced by stack effect. Yang *et al*. (2018) studied the smoke back-layering length in naturally sloping tunnel based on the brine water experiment and quantified the stack effect in smoke back-layering length model. The driving force to prevent the smoke backflow in downhill tunnel not only resist static pressure difference and stack effect. Du *et al*. (2018) argued that the stack effect was a significant flow resistance for smoke control system in a downhill tunnel, and the driving force to control smoke backflow was remarkably larger than that in horizontal tunnel. This critical driving force for preventing smoke backflow in inclined tunnel has been revealed by Li and Yang (2020a). Yi *et al*. (2014) found that the critical velocity (no smoke backflow) in inclined tunnel was different with that in horizontal tunnel which decreased as the tunnel slop increasing from downhill to uphill. Weng *et al*. (2016) dimensionless analyzed the critical velocity in inclined tunnel and proposed a dimensionless correlation to qualified the critical velocity for inclined tunnel. Jiang and Xiao (2022) suggested that the critical velocity in inclined tunnel should be considered based on the buoyant plume driven by buoyance or momentum. The influence of tunnel slop on critical velocity is small under momentum-driven plume, but that influence is large under buoyance driven plume. Jiang *et al*. (2021) considered the stack competitive effect between fire source two side in V-shaped slope tunnel. The stack effect in sloped tunnel are dominated by fire size and sloped angle of tunnel that brings difficulty to determine the critical velocity.

Most bifurcation tunnels, which is component units of Urban Traffic Link Tunnel (UTLT), have one or multiple slopes. The air flow in tilted bifurcation tunnel is more complex compared with in single-point slope tunnel due to the stack effect combined with the diverging flow and local resistance. The studies focused on smoke back-layering length in tilted bifurcation tunnel is scarce. 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 branch were affected by sloped bifurcation tunnel. That means the ventilation velocity to prevent smoke are varied with branch tunnel. Huang *et al*. (2020) proposed the empirical model to predict critical velocity model in branched tunnel, but not considered the tunnel slope. Li and Yang (2020b) investigated the driving force for preventing smoke in sloped bifurcation tunnel with uniform slope angle of mainline and ramp. The mainline tunnel and ramp always have varied slope angle and multiple slope combinations. However, the smoke back-layering length and critical velocity in sloped bifurcation tunnel is still not revealed and quantified clearly.

The purpose of this study is to investigate the smoke backflow behavior in branched tunnel with tilted downstream mainline region and horizontal upstream mainline region. The theory analysis is conducted to reveal the confrontation of buoyance and initial force. The numerical simulation was carried out to investigate the smoke back-layering length with varied tunnel slope and heat release rate. The mathematical model for smoke back-layering length in this titled downstream combined horizontal upstream bifurcation tunnel was proposed.

## 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 solves numerically a form of the Navier-Stokes equations 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.

The 1/20 small scale experimental results in 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 height, the mainline tunnel before shunting is 19m length with 0.675m width (including 4.0m extension region), the mainline tunnel after shunting is 10.86m length with 0.487m width, and the ramp is 9.23m length with 0.375m width. The small scale experiments with heat release rate 1.72kW, 3.45kW and 5.18kW 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 compared with numerical modelling. The temperature obtained by numerical modelling agrees well with the experimental results under quasi steady state, as shown in Fig.1. Thus, it is reliable using FDS to simulate the smoke movement in 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 (ratio of height difference *h* between tunnel tilt start point and tunnel exit to the horizontal tunnel projection distance *l* of inclined region) of mainline tunnel before shunting region 0% to 7% with interval 1% were considered. The test cases list in Table 1. First group presents a series conditions with the heat release rate varies from 3MW to 20MW, and the tunnel slope increase from 0% to 7%. To better distinguish the influence of bifurcation angle on smoke backflow in sloped tunnel, another group with three bifurcation angles 5°, 15° and 30° with tunnel slope 5% are established.

The fire source with dimension 1m×2m was located at joint node region 150m away from the right end of horizontal mainline tunnel. The fire source fuel was set as N-heptane, and the heat release rate were 3MW, 5MW, 10MW, 15MW and 20MW which represented the car, bus and truck fire (Ji *et al*., 2018). The material of tunnel wall was set as concrete with its thermal properties (density is 2280.0 kg/m3, specific heat is 1.04 kJ/ (kg K), conductivity is 1.8 W/(m K), emissivity is 0.9, 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 thermocouples were used to measure the temperature along mainline tunnel and ramp centerline. The thermocouple tree was installed near the fire source two sides 50m to measure the horizontal and vertical temperature. The interval of thermocouple tree was 2m. There are six thermocouples in each tree with vertical interval distance 1m, and the highest one was below tunnel ceiling 0.1m. Away from the fire source 50m, the thermocouple was placed 0.1m underneath the ceiling along longitudinal direction with interval 4m. The flow velocity and the pressure in tunnel was also measured. The time average value under quasi steady state was used in 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 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:

 (1)

where *D\** is the characteristic fire diameter, *Q* is the heat release rate in kW/m2, *ρa* is the ambient density in kg/m3, *cp* is constant pressure specific heat in J/ (kg·K), *Ta* is the ambient temperature in K, *g* is the gravitational acceleration in m/s2.

The previous studied suggested that the *δx* =0.1*D\** could obtain viable results (Tilley *et al*., 2012). The *D\** for least heat release rate in this study of 5MW is 1.8m. In order to save computation time and produce sufficient accuracy result, five mesh size between 0.1*D*\* two sides were adopted to analyze the independence, which were 0.5m, 0.4m, 0.3m 0.2m and 0.1m. The mesh independence analysis was conducted in branched tunnel with bifurcation angle 5° of this study. The heat release rate of fire source 5MW was selected and placed in joint node, the mainline tunnel slope is 3°. The longitudinal temperature along mainline tunnel centerline was selected as a criterion for sensitivity analysis, as shown in Fig.3. It is observed that the numerical result is not depend on the mesh size when the mesh is less than 0.3m. the corresponding proportion of *D\**/δ*x* is 6. Thus, in order to save the computational resource and output accurate result, the multi-domain mesh was conducted. The proportion of *D\**/δ*x* =6 was adopted to determine the mesh size between fire source two sides 50m, the mesh side in other region doubled.

## 3 Analytical modelling

The smoke movement is driven by initial momentum due to combustion heat. The thermal buoyancy induced by stack effect and the hydrostatic pressure would affect the smoke movement in branched slope tunnel. The bifurcation structure would influence the local resistance and turbulent the airflow. Fig. 4 shows the schematic diagram of smoke movement in branched tunnel with mainline positive slope and negative slope. The stack effect would be induced due to the density difference between smoke and air in slope tunnel. The smoke plume tilted towards to downstream tunnel portal. The influence of stack effect on smoke plume can be deemed as a virtual longitudinal ventilation from lower portal to higher portal. If the stack effect is relatively strong, which means the virtual longitudinal ventilation is comparative with smoke layer momentum, the smoke would not exhaust through lower portal and the smoke back-layering at upstream occurred. In addition, the virtual longitudinal ventilation achieved to critical value, that the stack effect is large enough, the smoke stagnation point of smoke is over fire source. Under circumstance, there is not smoke backflow at upstream that is conducive to smoke control and evacuation.

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

 (2)

where *Pstack,d* is the stack pressure in Pa, *L* is the mainline tunnel length before shunting in m, *ρs* is the smoke density in kg/m3, *β* is the inclination angle of mainline tunnel before shunting in degree, *V´* is the virtual velocity in m/s, h is the tunnel height difference between the tilt start point and tunnel exit in m, *l* is the tunnel projection distance of inclined region in m.

Based on the ideal gas low, the density difference can be expressed by temperature rise as *ρa*/*ρs* = *T*/*Ta*. Eq.(1) can be transferred as

 (3)

where *T* is the smoke temperature in K, △*T* is the temperature rise in K.

The smoke plume spreads in vertical direction and impinging the inclined tunnel ceiling, then propagates along tunnel ceiling, as shown in Fig. 5. The smoke movement in mainline tunnel upstream of fire source and in ramp can be seen as a horizontal tunnel. However, downstream of fire source, the smoke spreads in an inclined tunnel that caused the virtual wind velocity *V´* along tunnel. Thus, the smoke movement in vertical region can be seen as bending plume induced by ventilation. The cross section of vertical plume is assumed as circular with radius *r*, and the velocity and temperature profiles is 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 expressed as following.

 (4)

The conservation of momentum in vertical direction equals to buoyancy force induced by density difference. From the basic equation of ideal plume △*ρr*2=*Q*/π*vc*p*T*a, the momentum equation in vertical direction can be expressed as Eq. (5).

 (5)

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

 (6)

where *r* is the radius of plume in m, *v* is the trajectory velocity of plume in m, *δ* and *η* are the entrainment coefficients, *α* is the included angle between plume axis and slope floor surface in degree.

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

 (7)

where *C1* and *C2* are constants, *m* and *n* are power coefficients.

Submitted Eq. (6) and (7) into Eq. (4) and (5), then both sides of mass equation are divided by sin*α*. The following equations are given.

 (8)

Differentiate and Simplified the equation (8), the following function can be given

 (9)

The entrainment coefficient *η* is equal to *δ*cot*α*. The plume angle *α* is influenced by virtual wind due to static effect. In fact, the plume axis velocity is controlled by vertical velocity without wind-blown and the longitudinal wind velocity. The characteristic plume velocity relates to heat release rate, as given

 (10)

The dimensionless virtual wind velocity can be given *V*´*\**=*V´*/*w*. The sine *α* is a function of dimensionless virtual velocity, it can be referenced the plume angle under wind tunnel given as

 (11)

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

 (12)

The kinetic energy of plume breaks down into three parts after impinging the tunnel ceiling, which includes kinetic energy of smoke flow with same direction and opposite direction of static effect force, the other part transferred as thermal energy due to friction. Thus, after impingement, the smoke flow velocity near the tunnel ceiling are proportional to vertical velocity beneath tunnel ceiling. The fire source located at joint node region in present study. The one part of smoke would diverse to ramp, thus, the hot smoke in mainline tunnel assumed produced by effectively heat release rate *Qm*. The smoke flow velocity near impingement point is maximum value, it is given as

 (13)

where *uup,max* is the maximum smoke flow velocity opposite static effect direction after impingement in m, *C*3 is coefficient, *Qm* is effectively heat release rate in mainline tunnel which is in proportion to fire size and varied with bifurcation angle and slope degree, *Q*m=C4*Q*, C4 is coefficient less than 1, *H* is the tunnel height in m.

The smoke layer would be dragged to upper tunnel portal due to static effect. The smoke movement at upstream of fire source (horizontal region) is opposite with the virtual wind. The smoke would be backflow when the momentum of smoke layer larger than that of against wind, 1/2*ρs* *u2up,max*>1/2*ρV’*2.

The energy of backflow smoke layer 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. It is noted that the mass flow of reverse smoke layer is assumed constant *ρjuup,max*. The virtual wind induced by static effect only acts on smoke layer cross-section.

 (14)

where *ρ*j is the smoke density beginning reverse flow in kg/m3, λ is the frication coefficient, *ds* is the hydraulic diameter of reverse smoke layer in m.

Based on the boundary condition of *uup*=*uup,max* during *x*=0, Solving the integral Eq.(14) gives the smoke reverse flow velocity along tunnel.

 (15)

where *x* is the distance to fire source in m.

Based on the ideal gas law, the density relationship between wind and smoke can be expressed using temperature rise, *ρa*/*ρj* = *Tmax*/*Ta*. It is assumed that the reverse smoke maintains stable stratification, the thickness of smoke layer is fixed. Thus, the frontal region of reverse smoke stagnated during *uup*=0. The distance from frontal region stagnation point of reverser smoke layer to fire location is the smoke back-layering length. Based on *L*=*x* during *uup*=0, the smoke back-layering length can be obtained by solving the Eq. (15), given as

 (16)

where *C* is coefficient.

The hydraulic diameter of smoke layer is controlled by smoke thickness which varied 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, the Eq. (16) can be further simplified as

 (17)

where *a*, *b* and *n* are coefficients. The maximum smoke temperature *Tj* beneath the tunnel ceiling has been 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 mainline tunnel centerline under varied tunnel slope with bifurcation angle 5° is shown in Fig.6. In the horizontal tunnel, the velocity direction beneath the tunnel ceiling is towards to tunnel ends because of this velocity representing the smoke layer movement which dominated by buoyance force. However, the velocity direction in lower air layer leans towards to fire source due to the air entrainment. The velocity profile gradually inclined to mainline tunnel portal before shunting (upper exit) with the increasing of tunnel slope. The entrainment mechanism of combustion in bifurcation tunnel and the stack effect contributes to this inclined velocity profile. The cross-section space of tunnel between joint node two sides is not uniform. The fire source in present work located at joint node, thus, the air entrainment is asymmetrical. The cross-section space at side after shunting is larger than another side, more air is entrained to fire source through this section lower layer. The fresh air layer in side before shunting is thinner and less air entrainment into fire plume. However, the upper smoke layer is a little tilted to ramp direction near fire source also due to the relatively large cross section area in this direction. Thus, the curved vertical fire plume occurred in horizontal tunnel, and the vortex in direction after shunting is more obvious than that in side of mainline before shunting. This asymmetrical air entrainment between fire source two sides results in a slight inclined of smoke movement, which can be seen from longitudinal velocity profile in horizontal tunnel. This consists with previous experimental study (Huang *et al*., 2019). Under circumstance, no stack effect exists in horizontal smoke movement, only the asymmetrical entrainment induced the inclined flow. In fact, the inclination of smoke movement due to the asymmetrical entrainment is limited, as shown in Fig.6 (a).

In tilted tunnel, the velocity profile tends to upper portal direction more significantly than that in horizontal one. And the inclined degree nearby fire source area increased with tunnel slope, as well the velocity profile gradually filled up the tunnel cross-section. Under circumstance, the stack effect dominates the smoke inclined flow (Gao *et al*., 2022). The backflow velocity existed beneath the tunnel ceiling that indicates there are a thin smoke backflow layer at upstream when the tunnel slope is 3%. The airflow to fire source fills the main section at upstream lower layer. The velocity profile from fire source to upper portal fills the downstream tunnel cross section and the velocity near tunnel ceiling is higher because of the heat smoke layer dominated by stack effect and initial momentum. When the tunnel slope is 5% and 7%, only the unidirectional velocity to fire source fills the upstream section. That indicates the smoke backflow has been restrained due to relatively strong stack effect. For a given tunnel trajectory length, the height difference between the fire source and upper exit increased with larger tunnel slope that results in the stronger pressure difference *P*=*△ρgsinβL*. Thus, smoke layer backward flow at upstream of fire source fades away. Simultaneously, the entrainment flow at downstream lower air layer disappeared gradually and being filled with smoke flow under 5% and 7% tunnel slope.

Totally, unidirectional flow velocity from fire source to upper portal has been filled up the tunnel cross-section under tunnel slope 5% and 7%. The longitudinal ventilation filled up the tunnel cross-section from lower end inlet to smoke layer front stagnation point. That indicates the longitudinal wind in tunnel has been induced by stack effect, and the wind velocity increasing with larger tunnel slope. This induced longitudinal wind can confine the smoke backflow. The smoke back-layering has been confined in upstream outlet by induced wind during tunnel slope greater than 3%.

Fig.7 shows the airflow velocity in tunnel, the smoke movement velocity in branched slope tunnel are also influenced by heat release rate and bifurcation angle. For a given tunnel slope of mainline before shunting, the longitudinal velocity increased with the increasing of heat release rate shown in Fig.7 (a), and the thickness of smoke back-layer decreased because of the heat flux increasing that enhances the uphill buoyance force. For a given heat release rate, the greater longitudinal wind velocity in upstream horizontal region results from larger tunnel slope, and the induced longitudinal wind velocity slightly increased with the increasing of bifurcation angle as shown in Fig7 (b). The main reason maybe that the open area along longitudinal direction decreased at upstream with the larger bifurcation angle. Due to the flow direction changed and relatively more smoke entry to uphill region to enhance the buoyance force driving smoke flow under larger bifurcation angle. On the other hand, the entrainment air from ramp entrance to fire source needs to overcome greater local resistance and kinetic energy consumption, thus, more fresh air entrained from mainline horizontal end to balance pressure and combustion.

Fig.8 presents the dimensionless virtual wind velocity varied with sine of tunnel inclination and sine of bifurcation angle. Under the bifurcation angle 5°, the dimensionless virtual wind velocity defined as reference one *Vref´\** which keeps consistent for a given tunnel slope. The *Vref´\** can be well normalized using sin*β* expressed as Eq. (18). The larger bifurcation angle results in the higher dimensionless virtual wind velocity, which linearly increases with sin*θ*. The *V´\** under varied bifurcation angle are as numerator and *Vref´\** as denominator, the ratio of dimensionless virtual wind velocity against the sine of bifurcation angle is used to account for the bifurcation angle influence, as shown in Fig. (8). Thus, the relationship between dimensionless virtual wind velocity, tunnel slope and bifurcation angle is given as Eq. (19).

 (18)

 (19)

### 4.2 Smoke back-layering length in slope tunnel

For the horizontal mainline tunnel, the smoke is exhausted from mainline tunnel both two sides. With the increasing of the tunnel slope, the smoke stagnated at a distance from fire source in horizontal region due to the stack effect. And the smoke back-layering length decreased with the increasing of tunnel slope (Wan *et al*., 2019), as shown in Fig. 9. The smoke exhausted through mainline tunnel two ends during tunnel slope less than 3%, thus, the smoke backflow in whole upstream region. For a given tunnel slope, the smoke back-layering length slightly decreased with the increasing of heat release rate during tunnel slope greater than 4%. The reason of above results lies on the relative prevailingness of horizontal initial force to horizontal region portal and stack effect to upper end direction. Under the circumstance, the height difference between the fire source to upper end is relatively high, the stack effect increased faster compared with the horizontal initial force under stronger heat release rate. That the stack effect dominates the smoke movement to 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 conducted by Zhang *et al* (2021). claimed that the heat release rate has no significant effect on smoke back-layering length. Additionally, Oka (*et al*., 2013) suggested that the smoke back-layering length increases with the heat release rate and proportional to *Q*2/5 under natural ventilation. The reason may be that the difference of tunnel structure, the previous study conducted in a single point downhill tunnel but the present tunnel is a branched tunnel constructed with inclined mainline region, horizontal mainline region and ramp. The resistance loss of smoke backflow in horizontal region in present study is less than that in previous downhill tunnel, and the height difference also exits in previous downhill backflow region that induced the pressure difference but not exited in present upstream horizontal region.

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

For the tunnel slope 5%, the bifurcation angle increased from 5° to 30°, the smoke back-layering length is shorter and this difference increased with the fire power. The smoke will be radial spread after impinging on the tunnel ceiling, while the initial force pushed one part of smoke enters to ramp. With the increasing of bifurcation angle, the included angle of initial force in ramp and mainline tunnel increases and the effective cross-section in ramp for air entrainment along mainline tunnel decreases. Thus, the more air is entrained from horizontal mainline tunnel portal to balance the pressure difference induced by stack effect. Thus, the virtual wind flow in mainline tunnel increases and the momentum of reverse flow smoke in horizontal mainline tunnel decreases that results in the shorter smoke back-layering length under larger bifurcation angle.

The smoke back-layering length in branched tunnel are compared with the predictions by previous empirical model under natural ventilation condition (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 back-layering length in branched tunnel, and the heat release rate has not been taken into consideration. The empirical model of smoke back-layering length established by Wan *et al*. is based on the fire occurred in naturally tunnel with vertical shaft. That the smoke exhausted through uphill shaft which means the inclined length between smoke outlet and fire source is less than uphill tunnel end to fire source, thus, the stack effect in inclined region is weaken. On the other hand, the vertical shaft enhances the stack effect due to increase the height difference. The cooperation mechanical of weaken effect as reduced inclined length and enhancement effect of vertical height this is not applied to the present condition. Oka *et al* (2013) and Kong *et al* (2021) considered the effect of heat release rate on smoke back-layering length and the stronger heat release rate the longer smoke backflow distance for a given tunnel slope, while the smoke back-layering length has been over estimated in present conditions. Thus, the previous empirical expression for smoke back-layering length under natural ventilation is not applicable for the branched tunnel with tilted mainline tunnel before shunting. Then it is urgent to develop a new general correlation for the smoke back-layering length in branched tunnel with different mainline tunnel slope.

The non-dimension smoke back-layering length *L*/*H* are correlated using *Ta*/*Tj* (25sin*α*/48δ2sin*β*)2/3/*V*´\*2, as shown in Fig.11. The *L*/*H* is logarithmically related to the dimensionless parameter 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

 (20)

The smoke back-layering length calculated using Eq. (20) are compared with the numerical results. Fig.12 shows the smoke back-layering length can be well calculated using Eq. (20). It is noted that the present mode is applicable for branched tunnel with inclined downstream mainline region combined with horizontal upstream mainline region. For the branched tunnel with whole tilted mainline, the buoyance force in tilted upstream would be enhanced and the smoke reverse flow distance being weakened, which will be studied in further 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 back-layering length is specifically focused. The empirical model for predicting the virtual wind velocity and smoke back-layering length was developed taking the tunnel slope and bifurcation angle into consideration. The major conclusions are as follows:

(1) The flow velocity along mainline is influenced by tunnel slope significantly that larger wind velocity occurs from the horizontal entry to upper exit under higher mainline tunnel slope. The wind velocity is also strengthened by greater heat release rate due to the buoyancy force enhanced the stack effect. The bifurcation angle has a limited impact on the wind velocity which is well correlated using sine of bifurcation angle. The dimensionless wind velocity correlated well using the 2/5 power sine tunnel slope, and linearly increased with bifurcation angle.

(2) The longitudinal temperature in horizontal mainline region decreased with the increasing of tunnel slope. The distance from the temperature drop point to fire source is shorter with larger tunnel slope due to the stagnation position of smoke layer near fire source.

(3) With the higher difference between fire source to upper mainline exit, the smoke back-layering length is shorter. The smoke backflow distance is reduced under the larger bifurcation angle and stronger fire size as the more smoke being pushed to uphill region with stronger buoyancy force. A new non-dimension predicted model for smoke back-layering length in branched tunnel with tilted mainline region before shunting but horizontal mainline region and ramp after shunting is proposed, which includes the effect of tunnel slope, bifurcation angle and heat release rate on smoke backflow distance.

## CRediT authorship contribution statement

**Youbo Huang**: Funding acquisition, Conceptualization, Formal analysis, Methodology, Writing - original draft. **Xi Liu**: Data curation, Writing - original draft, Writing - review & editing. **Bingyan Dong**: Investigation, Writing - review & editing. **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 paper.

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