**Investigation of the Fire Hazard of Underground Space Fire Scenarios in Urban Metro Tunnels under Natural Ventilation: Analysis of the Impact of Tunnel Slope on Smoke Back-Layering Length**

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# Abstract

The smoke back-layering length is a crucial parameter for evacuating people in both road and subway tunnel fires. This study investigates the fire hazard induced by carriage fire in inclined metro tunnels under natural ventilation. The parameter 'transition slope' is defined to measure the smoke flow from the carriage head in the upstream direction to the tunnel or not due to the stack effect of the tunnel slope. The aim of this paper is to analyse the effects of changes in cross-section, downstream length, tunnel slope, and carriage side-door coupling on smoke behaviour characteristics by experiment and simulation methods. A piecewise function expression between dimensionless smoke back-layering length, downstream length, and tunnel slope for carriage fires in an inclined tunnel under natural ventilation is proposed by theoretical analysis. At the same time, a 1:15 scale model experiment was conducted to initially analyse the characteristics of smoke movement. Following this, full-scale numerical simulations were employed to complement the model experiment and quantify the principles governing smoke movement. The experimental results show that the tunnel slope has a significant effect on the smoke back-layering length. In contrast, the influence of the heat release rate was found to be relatively minor. In addition, simulation results show that the tunnel slope has no significant effect on the smoke back-layering length when the fire location is approximately 20 m from the train head, and the tunnel slope is in the range of 2.29° ~ 3.43° (4% ~ 6%). For small tunnel slopes, smoke spreads in the tunnel, and the smoke back-layering length produced by the virtual fire source shows a different law from the previous study model. Finally, the correlation coefficient of the piecewise function in theoretical analysis is fitted by combining the experimental and numerical simulation results.

**Keywords:** Inclined metro tunnel; Tunnel fire; Smoke back-layering length; Fire source location; Transition slope; Natural ventilation.

|  |  |  |  |
| --- | --- | --- | --- |
| **Nomenclature** | | *H* | Hydraulic diameter (m) |
| *Q* | Heat release rate (kW) | *Vc* | Critical velocity (m/s) |
| *Q\** | Dimensionless heat release rate | *T0* | Ambient temperature (K) |
| *L* | Smoke back-layering length (m) | *u0* | Ambient velocity (m/s) |
| Δ*P* | Pressure difference induced by stack effect (Pa) | *L\** | Dimensionless smoke back-layering length (m) |
| *Qu* | Equivalent fire source (kW) | *T∞* | Ambient air temperature (K) |
| *g* | Gravitational acceleration (m/s2) | *Ldown* | Downstream length (m) |
| *Lf* | Distance between the fire source and the front of the train (m) | *cp* | Specific heat capacity of air (kJ/kg‧K) |
| ΔTmax | Maximum temperature rise (K) | x | Distance from the measure point to the fire source (m) |
| *Vin* | Longitudinal induced airflow velocity (m/s) | *Greek letters* | |
| *ρ∞* | Ambient density (kg/m3) |
| *Ri* | Richardson number | *α* | Tangent of the slope angle (°) |
| *K* | Coefficient for stack effect (–) | *Subscripts and subscripts* | |
| *h* | Distance above the reference (m) | \* | Dimensionless expression |
| *Vin-train* | Train ventilation velocity (m/s) | *train* | Train |
| *D* | Fire source diameter (m) | *tran* | Transition condition |

# Practical application

This study provides valuable insights into the practical implications of controlling and mitigating the impact of fires in inclined metro tunnels. By understanding the critical role of tunnel slope and providing a quantitative tool for smoke spread law assessment, this study contributes to the enhancement of safety measures and the protection of lives in tunnel environments during fire incidents.

# 1. Introduction

As the most effective transportation method to alleviate road traffic congestion in a metropolis, metro systems have developed rapidly 1. Due to the special structure of the metro tunnel, double-length and narrow, metro tunnel fire has more threat to the life of people 2. Fire accidents have occurred globally, leading to significant human and property losses. For instance, the Daegu underground fire in 2003 resulted in 192 fatalities and 151 injuries, whereas an underground arson incident in Hong Kong in 2017 caused 18 injuries 3, 4. Most of the people who died were killed by poisonous smoke, according to accident investigations. Hence, it is necessary to study the smoke flow characteristics in metro tunnels. The smoke back-layering length is a key parameter for people's evacuation in tunnel fires 5-7. Research on smoke back-layering length has been widely reported.

Tang, Li 8 conducted experimental research on smoke back-layering in a tunnel using ceiling extraction along with longitudinal ventilation. They examined six distinct longitudinal ventilation velocities along with the corresponding ceiling extraction flow rates. Their findings demonstrated a consistent trend where higher longitudinal ventilation or ceiling extraction velocities decreased in the smoke back-layering length. A simple model was proposed to predict the smoke back-layering length. For different tunnel structures, Yang, Luo 9 conducted a series of fire tests using a 1/10 scale branched tunnel to examine the smoke back-layering length in different tunnel structures. Their experiments explored various factors, including longitudinal ventilation velocities, heat source locations, and heat release rates. The results indicated that the dimensionless smoke back-layering length, *L/H*, correlates with the expression *gHQ/ρ0cpT0v3A*, which aligns with Thomas's findings 6. Furthermore, as the longitudinal ventilation velocity increased sufficiently, a downstream deflection in the maximum smoke temperature was observed. Huang, Li 10 conducted experiments to examine the impact of bifurcation angle on smoke movement in branched tunnel fires under longitudinal ventilation. Their findings revealed that, for a constant heat release rate, an increase in longitudinal ventilation velocity led to a reduction in the smoke back-layering length. Additionally, they developed an empirical model for smoke back-layering length that takes into account the bifurcation angle.

In real situations, the stack effect has an important influence on the smoke back-layering length in inclined tunnels 11, 12. Some scholars have conducted studies on the factors influencing smoke spread in inclined tunnels. Wan, Gao 13 comprehensively conducted a thorough investigation of smoke flow behaviours in inclined tunnel fires featuring a shaft. Their study placed particular emphasis on the impact of tunnel slope on temperature distributions within both the shaft and tunnel, as well as on the smoke back-layering length and tunnel inlet air velocity. The results demonstrated that increasing the slope had the dual effect of reducing plug-holing and decreasing smoke temperatures in the inner region of the shaft. They established a correlation indicating that the tunnel inlet air velocity increased with steeper tunnel slopes and decreased when the fire source was located further from the downhill tunnel inlet. Jiang and Xiao 14 tackled the problem of critical velocity theoretically, experimentally, and numerically in inclined tunnels. The results show that the influence of the tunnel slope on the critical velocity was not affected by the heat release rate.

In addition to studies in ordinary tunnels, some scholars have investigated smoke behaviour characteristics in metro tunnels. Hu, Zhang 15 experimentally studied the characteristics of critical control parameters induced by carriage fire in a longitudinally ventilated metro tunnel. It was found that the transition velocity was about 0.9 times the magnitude of the critical velocity, and a model of the smoke back-layering length induced by carriage fire was proposed. Zhang, Yao 16 investigated the smoke back-layering length caused by an electrical train fire in a metro tunnel. A model to predict the smoke back-layering length was proposed by taking the transition point when the smoke overflows the train as the demarcation point based on the equivalent fire source method. However, smoke movement in the carriage and the influence of the tunnel slope are not considered. Wang and Gao 17 conducted numerical simulations to study the impacts of metro train blockages on critical velocity in inclined metro tunnels. The critical velocity is obtained using a curve that extended until the smoke back-layering length is equal to zero. The influence of 10 slopes from 0.5% to 5% (0.28° ~ 2.86°) on the critical velocity was analysed. However, the influence of the transition point of smoke overflowing from the train on the critical velocity is not considered.

Previous studies have investigated the factors that influence smoke back-layering length. However, there are some differences between the subway fire scenarios. First, the double long-narrow structure complicates the smoke flow. In the case of a fire in a train, the smoke first impinges on the train ceiling. One part of the smoke spreads along the longitudinal direction. Another part of the smoke reaches the tunnel ceiling through side doors 18, 19. A previous study has shown that the back-layering length in a train is longer than that in a tunnel-blocking area 20. Therefore, it is important to study the smoke spread inside the train. Second, the coupling effect of the side doors can produce a shorter smoke back-layering length than that of an ordinary tunnel 20. Third, smoke would overflow the train and continue to spread upstream in a metro tunnel with a small tunnel slope under natural ventilation 21. The back-flowed smoke gas front might be stopped inside the train carriage in some extreme cases of large tunnel slopes, such as the transition section of the subway line from the aboveground platform to the underground station 17.The transition point is used to determine whether the smoke would stop in the train or the tunnel in the upstream direction. In this study, the slope of this transition point is defined as the transition slope based on the previous definition of transition velocity 15, 22. It can be used to judge the smoke descending in the train and the scope of the safe area, and to determine the safe evacuation time for the personnel in the train to walk to the train head and evacuate from the upstream direction. Hence, it is necessary to study the influence of cross-sectional change and tunnel slope on the smoke back-layering length.

This study establishes the expression for the transition slope and smoke back-layering length induced by a train fire in an inclined double long-narrow space under natural ventilation. A series of scaled model experiment measurements and numerical simulations were conducted on smoke propagation in carriage fire scenarios for a train stopped in an inclined metro tunnel.

The results could refer to the emergency rescue of a stopped train fire in an inclined metro tunnel.

# 2. Theoretical analysis

In fact, in inclined tunnels under natural ventilation, stack effect plays a role of mechanical ventilation to make the smoke front stop at a certain point 23. With a decrease in tunnel gradient, the point at which the smoke front comes to a halt gradually shifts from within the carriage to further into the tunnel. Fig. 1 shows the schematic of smoke back-layering length with the fire source located in the middle of the carriage for different tunnel slopes while maintaining the same downstream length. For a large tunnel slope, the back-flowed smoke gas front might be stopped inside the train in the upstream direction as shown in Fig. 1(a). With the tunnel slope further decreasing, the back-layered smoke gas would penetrate the train through the emergency evacuation door and stop in the tunnel with a low velocity as shown in Fig. 1(b). There is a transition point in the process of smoke overflowing the train, that is, the smoke back-layering length is equal to the distance from the fire source and the train head as shown in Fig. 1(c).



(a)



(b)



(c)

**Fig. 1.** Schematic of smoke back-layering in the inclined metro tunnel: (a) large tunnel slope: smoke stopped in the train, (b) small tunnel slope: smoke stopped in the tunnel, (c) transition slope point.

# 2.1. Smoke Back-Layering Length for Smoke Gas Front Stopped in the Train (*L* ≤ *Lf*)

The back-flowed smoke gas front might be stopped inside the train with a large tunnel slope, which is shown in Fig. 1(a). In this condition, the train carriage can be treated as short-distance tunnel to study the smoke movement in the carriage due to the heat flow rate of the side door is far less than the heat release rate 19.

Scholars have conducted studies on influencing factors of smoke back-layering length in tunnels under longitudinal ventilation. Thomas 6 proposed a prediction model for the smoke back-layering length in a longitudinally ventilated horizontal tunnel. A dimensionless smoke back-layering length prediction model was proposed.

 (1)

Vantelon, Guelzim 24 carried out a series of model experiments to study the smoke back-layering length in a 1.5m long semicircular pipe. The results show that the dimensionless smoke back-layering length is related to the 0.3 power of the modified Richardson number. Concurrently, the tunnel cross-sectional area, denoted as *A*, can be represented by a quadratic function of the tunnel height *H*.

 (2)

*Ri*, a dimensionless parameter, serves to describe smoke back-layering length. Notably, *Lb*, representing the smoke back-layering length, exhibits dependencies on multiple factors, including heat release rate (*Q*), ambient air density (*ρ∞*), specific heat of air at constant pressure (*cp*), ambient temperature (*T∞*), gravitational acceleration (*g*), longitudinal mechanical ventilation velocity (*V*), and tunnel height (*H*).

Li, Lei 5 conducted experimental tests to investigate the critical velocity and the smoke back-layering length in tunnel fires. Based on the experimental data, a correlation that takes 0.15 dimensionless heat release rate as a transition point to predict the smoke back-layering length was proposed.

 (3)

The previously mentioned studies primarily address fire scenarios within longitudinally mechanically-ventilated tunnels. In contrast, for inclined tunnels without ventilation systems, the longitudinal mechanical ventilation velocity *V* can be substituted with the upstream inlet airflow velocity *Vin* induced by the stack effect. Kong, Xu 23 conducted a numerical simulation to predict the impact of downstream length and tunnel slope on the smoke back-layering length in a 4% (2.29°) slope tunnel under natural ventilation. Based on the theoretical analysis and simulation results, they concluded that *Vin* could be expressed as*Vin*=*f*(*α, L*down), and the dimensionless smoke back-layering length is logarithmically correlated with the cubic power of the downstream length.

 (4)

In light of the preceding analysis, it becomes evident that the smoke back-layering length within the carriage is intricately linked to the Reynolds number (*Ri*). For smoke control in the metro carriage, a double long-narrow space is formed in the tunnel and train. In this condition, the smoke back-layering length *L* is determined by tunnel slope *α,* heat-release rate *Q* and train ventilation velocity *Vin-train* induced by the stack effect. Based on the Reynolds number (*Ri*), this function can be expressed as:

 (5)

In a longitudinally ventilated double-narrow space, the longitudinal ventilation velocity was related to the train ventilation velocity. The proposed relation can be expressed as follows:

 (6)

By incorporating Eq. (5) and Eq. (6), the Richardson number in Eq. (5) was revised by replacing train ventilation velocity *Vin-train* with longitudinal induced airflow velocity *Vin* induced by the stack effect. At the same time, the induced *V*in caused by the stack effect can be influenced by the upstream or downstream length *L*down and the tunnel slope α, and can be represented as *V*in = *f*(α, *L*down). At the same time, scholars have extensively verified that longitudinal-induced airflow is a crucial factor affecting smoke movement and airflow distribution in inclined tunnels 13, 23. The longitudinal-induced airflow caused by the stack effect is mainly determined by the temperature difference and height difference. This function can be expressed by Eq. (7):

 (7)

From Eq. (7), there are two special cases in inclined tunnels. One is the fire source is infinitely close to the downstream outlet (*Ldown*= 0); the other is the tunnel slope is zero (*α* = 0). In both cases, the driving force Δ*P* of smoke movement caused by the stack effect is zero. Therefore, corresponding points are added in the process of determining induced airflow velocity to represent that the induced airflow speed is zero. The dimensionless smoke back-layering length in the train carriage can be transformed into:

 (8)

Eq. (8) represents the determination of the smoke back-layering length, *Lb*, in inclined metro tunnels is a function of *Ri*, where the key parameters include tunnel slope (*α*), heat release rate (*Q*), and downstream length (*Ldown*). Subsequently, experimental and numerical data will be utilized to formulate an empirical correlation for predicting the dimensionless back-layering length under different fire source locations.

# 2.2. Smoke Back-Layering Length for Smoke Gas Front Stopped in the Train (*L* > *Lf*)

For an inclined tunnel, there would be a transition slope point in the process of smoke penetrating the train, that is, the smoke back-layering length is equal to the distance from the fire source and the train head, which is shown in Fig. 1(c). With the tunnel slope further decreasing, the back-layered smoke gas would penetrate the train through the emergency evacuation door and stop in the tunnel with a low velocity, which is shown in Fig. 1(b). The dimensionless back-layering length cannot be described as the above equations in section 2.1 of this paper because the cross-section area of smoke flow has changed from the train carriage section to the tunnel section.



**Fig. 2.** Schematic diagram of equivalent fire source method.

Based on the method of the virtual fire source, the smoke back-layering length can be divided into two parts, as shown in Fig. 2 16. One is the smoke back-layering length *L*st in the train produced by the equivalent fire source *Qt*; the other is the smoke back-layering length *Lu* in the tunnel without the metro train produced by the equivalent fire source *Q*u. This dimensionless relationship can be expressed as follows:

 (9)

The heat release rate of the equivalent fire source *Qu* can be obtained using the maximum ceiling temperature model of a single tunnel 25. The maximum temperature of the ceiling is that of the smoke at the lower boundary of the tunnel, which corresponds to the position of the train end. At the same time, the effective height at the location of the equivalent fire source *Qu* is *H*tunnel.

 (10)

To obtain the heat release rate of the equivalent fire source *Qu*, the function can be transformed into:

 (11)

Similarly, according to Eq. (8), the smoke back-layering length (*Lu*) provided by the virtual fire source *Qu* in the inclined metro tunnel can also be considered as a function of the *Ri* number, which is expressed as:

 (12)

# 3. Model experiment

# 3.1. Model design

Based on the space dimension of the Beijing subway tunnel, a simplified small-scale metro tunnel (1:15) experimental model was established according to the Froude scaling method, whose accuracy of simulating buoyancy driven flow issues has been widely validated 26. The correlation of the scaling rules is listed in Eq. (13):

 (13a)

 (13b)

 (13c)

where *Q* represents heat release rate, *l*, *T* and *V*, denote length, temperature and velocity. The scaled tunnel, which is 21 m long, 0.675 m wide, and 0.5 m high, represents a full-scale tunnel that is 315 m long, 10.125 m wide, and 7.5 m high. The tunnel was divided across three parts: upward sloping segment (Region I), a horizon segment (Region II), and a downward sloping segment (Region III), whose cross sections are all rectangular, as shown in Fig. 3. A soft connexion is used between the two regions to reduce air loss to the ambience. The experiments were conducted in Region I to investigate the smoke movement in an inclined metro tunnel. Simultaneously, the observation window in Region II was opened to ensure that the inlet and outlet of Region I have the same atmospheric environment.



(a)



(b)

**Fig. 3.** Schematic of the experimental model and measurement apparatus. (a) schematic diagram, (b) experimental model.

To reveal the evolution characteristics of smoke back-layering length for inclined tunnel environments induced by carriage fires, the experimental train was placed 1 m away from the downstream to give a long upstream smoke spread space. In order to maintain consistent spacing proportions between the subway side doors and the tunnel walls, the subway model was placed horizontally due to the tunnel width of the experimental model exceeds its height. The metro train is 1.2 m long, 0.328 m wide, and 0.146 m high, with a cross-sectional area of 0.047 m2, representing an actual cross-sectional area of 10.6m2. At the same time, the door size is set according to the opening rate of the actual train doors. It was equipped with six side doors that were 8 cm wide and 9.8 cm high and were spaced 12 cm apart. In addition, it had two emergency evacuation doors that were 15.7 cm wide and 8.2 cm high. The sidewall of the metro train was built of galvanised steel sheet with a thickness of 3 mm. The front sidewall of the tunnel was covered by fire-resistant glass with a thickness of 5 mm to photo the smoke spreading process clearly during the experiment. The other sidewall of the tunnel was built of galvanised steel sheet with a thickness of 5 mm. The roof of the house was placed with a fixed pulley, which can be used to adjust the tunnel slope steadily by pulling the chain.

K-type sheathed thermocouples were used to measure the ceiling temperatures, and the smoke back-layering length can be obtained from the ceiling temperature distribution 27. Their precision and reaction time are 0.1 ℃ and 1 s, respectively. 30 thermocouples were installed 1 cm beneath the train ceiling with 4 cm intervals mounted along the longitudinal centerline of the carriage. Besides, 40 thermocouples were also placed below the tunnel ceiling with an interval of 25 cm. Nine hot-wire anemometers (TSI9515) were placed uniformly in the tunnel cross-section to measure the inlet airflow velocity induced by the stack effect. The accuracy of the anemometer is 0.01 m/s. Two Sony FDR-AX45A digital cameras with 4 megapixels were used to record the smoke movement of the metro carriage fire. One was used to obtain the smoke movement video of the side doors, and the other was used to obtain the smoke movement video of the upstream, both of which were used to further analyze the smoke movement characteristics.

A methanol pool was used as the fire source to simulate the fire scenarios in the carriages 28, 29. Four types of square pans of 10 cm×10 cm, 15 cm×15 cm, 20 cm×20 cm and 25 cm×25 cm were used. Each pan was 2 cm high and made of 2 mm thick steel plates. 99.0% - 99.5% fuel initial depth was maintained at 1 cm before each experiment. The fuel real-time masses were recorded dynamically by an electronic balance with an accuracy of 0.1 g. Thus, the fire heat release rate (HRR) could be calculated based on the mass loss rate at a steady stage together with the combustion heat of 19.93 kJ/g 30. The HRR was calculated using a specific formula as Eq. (14):

(14)

where is the average mass loss rate of liquid fuel during the quasi-steady stage (g/s); χ is the combustion efficiency. Additionally, all the experiments were carried out under the ambient temperature is about 15 ± 3 ℃. A total of 12 tests were conducted to obtain the smoke back-layering lengths under different fire heat-release rates and tunnel slopes in the inclined tunnel. To better facilitate evacuation, all the train side doors are set to open 20. The fire source was placed in the middle of the train to represent the typical situation of a metro tunnel fire. Each experimental scenario was repeated three times, and the uncertainty can be calculated by averaging the results of the repeated tests using *Xi = l* ± 2*σ*, where *l* is the mean value, and *σ* is the standard deviation 14. It is worth noting that due to the limitation of the experimental equipment, the influence of the fire source location on the back-layering length is not considered. The experimental conditions are summarised in Table 1.

**Table 1** Experimental conditions of metro tunnel train fire.

|  |  |  |  |
| --- | --- | --- | --- |
| Test no. | Fire heat release rate (kW) | Tunnel slope | Downstream length (m) |
| 1 - 3 | 2.29 | 2.29°, 3.43°, 4.57° | 1.6 |
| 4 - 6 | 3.44 | 2.29°, 3.43°, 4.57° |
| 7 - 9 | 4.59 | 2.29°, 3.43°, 4.57° |
| 10 - 12 | 5.74 | 2.29°, 3.43°, 4.57° |

# 3.2. Experimental results and analysis

The smoke spreads both upstream and downstream upon hitting the carriage ceiling, and infiltrates the tunnel through the emergency evacuation doors. The induced air flow generated in the inclined tunnel counters the upstream movement of smoke originating from the fire source. Fig. 4 shows the typical smoke flow configuration at upstream captured by the laser sheet under *Q* = 4.59 kW, *α* = 3.43°. The smoke back-layering length can be easily measured with a ruler. Due to the stack effect, within 10s of ignition, the smoke first spreads asymmetrically along the train carriages. Part of the smoke flow overflows from the downstream doors and impinges the tunnel ceiling. The smoke layering thickness inside the carriage begins to increase after the upstream smoke is blocked by the emergency evacuation door area at 158s. Simultaneously, a small part of the smoke flow overflows from the upstream side doors. As a further trend is that after 330s, the smoke will pass through the emergency evacuation door and stop in the tunnel. The case (Fuel pan: 20 cm × 20 cm, *Q* = 5.74 kW, *α* = 2.29°) was randomly selected as an example to demonstrate the data analysis process, as shown in Fig. 5. The temperature data used to determine smoke back-layering length of each case is extracted from the time-averaged value (330 s – 630 s) of the quasi-steady stage, see Fig. 5.

Due to limitations in the experimental conditions, it was not possible to provide a sufficiently steep tunnel slope to cause the smoke front to come to a stop in the carriage. Therefore, in the experimental results, the smoke front always comes to a stop in the tunnel. The dimensionless smoke back-layering length of the virtual fire source from the average experimental data between 330 s and 630 s is summarised in Table 2. The fire heat release rate (*Q*) was calculated by Eq. (14) and the virtual fire source heat release (*Qu*) rate can be calculated by Eq. (11). Results show that the tunnel slope has a significant effect on the smoke back-layering length. Simultaneously, the comparisons between four heat release rates show that the influence of the heat release rate on the smoke back-layering length is relatively small under the same tunnel slope. Generally, it is acceptable to ignore the influence of heat release rate on smoke back-layering length from the perspective of engineering applications 31, 32. Therefore, the influence of heat release rate on the smoke back-layering length is not considered in the following study.

**Table 2** `Dimensionless smoke back-layering length of virtual fire source from model experiments.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Test no. | *Q* (kW) | *α* | Δ*T*max(K) | *Q*u (kW) | *L*u\* | Test no. | *Q* (kW) | *α* | Δ*T*max(K) | *Q*u (kW) | *L*u\* |
| 1 | 2.29 | 2.29° | 32.57 | 0.449 | 7.83 | 7 | 4.59 | 2.29° | 52.06 | 0.907 | 8.21 |
| 2 | 2.29 | 3.43° | 31.68 | 0.430 | 6.34 | 8 | 4.59 | 3.43° | 49.83 | 0.849 | 5.59 |
| 3 | 2.29 | 4.57° | 28.87 | 0.374 | 4.48 | 9 | 4.59 | 4.57° | 45.67 | 0.745 | 4.11 |
| 4 | 3.44 | 2.29° | 39.08 | 0.590 | 8.21 | 10 | 5.74 | 2.29° | 66.02 | 1.295 | 7.83 |
| 5 | 3.44 | 3.43° | 38.13 | 0.568 | 5.97 | 11 | 5.74 | 3.43° | 63.51 | 1.222 | 5.97 |
| 6 | 3.44 | 4.57° | 30.26 | 0.502 | 4.85 | 12 | 5.74 | 4.57° | 58.77 | 1.088 | 4.48 |



**Fig. 4.** The smoke movement process under Q = 4.59 kW, α = 3.43°.



**Fig. 5.** Data reduction and extraction for characteristic ceiling temperature.

# 4. Numerical simulation

**4.1. Fire dynamics simulator**

This study employs Fire Dynamics Simulator (FDS) Version 6.6 codes developed by NIST for building the numerical model to improve and expand upon the model experiments 29. Moreover, its capacity to simulate various building fire scenarios has been widely verified through multi-scale fire experiments 33, 34.

FDS employs numerical methods to solve a variant of the Navier–Stokes equations governing thermally-driven flow. It incorporates both the DNS (Direct Numerical Simulation) model and the LES (Large Eddy Simulation) model. For this study, the LES model, extensively utilized in examining fire-induced smoke flow behavior, has been chosen. Turbulent eddies responsible for mixing and large-scale motions are derived through filtering operations applied to the momentum and energy equations, resulting in equations governing the transport of large-scale momentum and thermal energy. The governing equation is as follows35:

 (15)

In terms of mass conservation, the conservation of momentum is:

 (16)

and the conservation of energy is:

 (17)

Radiative heat transfer, recognized as the primary mode of heat transfer in medium or large-scale fires, plays a crucial role in shaping the progression of fires and the dispersion of smoke. In this research, radiative heat transfer is incorporated by solving the radiation transport equation (RTE) using the Finite Volume Method (FVM). The RTE applicable to an absorbing or emitting and scattering medium is formulated as follows:

 (18)

within FDS, the convective heat flux () is derived through a fusion of natural and forced convection correlations:

 (19)

 (20)

where *h* is the heat transfer coefficient, *Tw* and *Tg* are the wall surface temperature and the gas temperature, *C*1 is the coefficient for natural convection and *C*2 is the coefficient for forced convection, *Lc* is a characteristic length and *k* is the gas thermal conductivity. Combining Eqs. (19) and (20), the parameters *h* and can be determined.

# 4.2. Numerical scenarios

In this study, to simulate a metro train fire in an inclined tunnel under natural ventilation, the model was built with a tunnel and a type B metro train consisting of 6 carriages. A schematic of the FDS model is shown in Fig. 6. The tunnel model is 500 m long, 4.8 m wide, and 5.2 m high. The metro is located 15 m from the downstream outlet at the higher end with a dimension of 120 m (length) × 2.8 m (width) × 3.8 m (height) and a cross-sectional area of 10.6 m2. The net height of each carriage is 2.2 m, including four side doors on both sides. In this study, the side doors (1.5 m wide and 1.8 m high) on one side and the emergency evacuation doors (1.2 m wide and 2.2 m high) at both ends were opened to simulate the evacuation situation 19. The materials of the metro train and tunnel were specified as “Steel” and “Concrete” in the simulation, respectively. The thermal properties of the materials are summarised in Table 3.

**Table 3** Thermal properties of the material.

|  |  |  |  |
| --- | --- | --- | --- |
| Material | Density (kg/m3) | Specific heat (kJ/(kg·K)) | Conductivity (W/m·K) |
| Concrete | 2280 | 1.04 | 1.80 |
| Steel | 7850 | 0.46 | 45.8 |



**Fig. 6.** Schematic of the metro tunnel model.

Flammable luggage carried by passengers is a potential cause of train fires. At present, the use of flame retardant materials in subway trains is now common practice and has been proven effective in limiting the train fire size 20, 36. Therefore, the T-Square fire was adopted for the fire growth, and the heat release rate (HRR) of the fire was set to 5 MW. According to Eq. (13a), this represents an HRR of 5.74 kW in the model experiment, also signifying the maximum fire heat release rate in metro tunnel fires 37. A cuboid fire source with dimensions of 2 m (length) × 1.8 m (width) × 0.2 m (height) was positioned on the centerline of the train floor, and the burning area was 3.6 m2. In this study, the position of the train is fixed, and the downstream length is varied by changing the location of the fire source inside the train carriage. Various fire locations and tunnel slopes are considered. With a spacing of 20m, five fire source locations are selected within a downstream length (*L*down) ranging from 35m to 115m between the fire source and the downstream outlet. At the same time, seven tunnel slopes are selected with intervals of 0.57°, ranging from 1.15° to 4.57° (2% ~ 8%). Furthermore, we explored 8 conditions from NS-36 to NS-43, incorporating different heat release rates and tunnel slopes. This was done to further validate the applicability of the results under varying heat release rates. The tunnel slope can be obtained by decomposing the gravity acceleration in the tunnel's longitudinal and height directions 32. The simulation scenarios are designed as summarised in Table 4.

**Table 4** Detail simulation cases for the train fire.

|  |  |  |  |
| --- | --- | --- | --- |
| Simulation case | Fire heat release rate (kW) | *L*down (m) | Tunnel slope |
| NS-1~NS-35 | 5000 | 35, 55, 75, 95, 115 | 1.15°, 1.72°, 2.29°, 2.86°, 3.43°, 4.00°, 4.57° |
| NS-36~NS-43 | 2000, 3000 | 55, 95 | 1.72°, 4.00° |

A set of horizontal thermocouples was installed 0.05 m below the train and tunnel ceiling. There are 119 thermocouples inside the train and 195 thermocouples inside the tunnel. The thermocouple interval of the train and tunnel is 1 m and 2 m, respectively. Nine velocity measuring points are evenly arranged 1 m away from the cross-sectional position to measure the induced airflow velocity in the longitudinal direction. To ensure consistency with the environmental conditions in the model experiment, throughout the FDS simulation, the environmental temperature for all simulations was set at 289.15 K, the environmental pressure of 101.325 kPa, and the smoke concentration was 0 at the initial time. Both the left and right portals are set as “OPEN” with natural ventilation conditions. The simulation time was set to be 1500 s to ensure the smoke movement is in a quasi-steady state.

# 4.3. Grid independence and model validation

Grid size is a critical factor to be considered to obtain viable results. The generally accepted grid size (*dx*) is between *D\**/16 and *D\**/4, which has been tested and verified by the American National Institute of Standards and Technology 38, 39. The characteristic fire diameter *D\** can be calculated by Eq. (21):

 (21)

Fig. 7 shows a schematic diagram of the grid. Based on previous research on tunnel fires, a grid size of approximately 0.1*D*\* has been employed within a large area near the fire source. For areas with fires at a greater distance, it has been reported that grid sizes twice as large or even larger are acceptable. In this study, the near fire region is defined near the train area. According to the recommended *D\** range, the grid size for fires ranging from 2MW to 5MW is between 0.16m and 0.24m. The tunnel area is considered as the area far away from the fire source, and the grid size is set to twice that of the near fire source area. Therefore, the tunnel was divided into three sub-domains: the domain on the left side of the train near the entrance is referred to as the “Left domain”, the domain containing the train is called the “Middle domain”, and the domain on the right side of the train near the exit is called the “Right domain”. The Left and Right domains are collectively referred to as the “Other domain”. The lengths of the three domains were 355 m, 130 m and 15 m, respectively. Fig. 8(a) shows a typical grid size independence analysis between four mesh systems in the area near the fire source (± 60 m near the fire source) for *Q* = 5 MW, *α* = 0°, *L*down = 75 m. A total of 4 different grid sizes rangeing from 0.16 m to 0.24 m in the middle domain were selected for the grid independence. The results show that there is no significant difference between the two curves with grid sizes of 0.16 m and 0.18m in the middle region. To save computing time, the grid size of the middle domain was set to 0.18 m, and the grid size of other domains was set to 0.36 m.



Fig. 7. A schematic diagram of the grid.

The Courant-Friedrichs-Lewy (CFL) criterion in FDS is employed to validate numerical convergence. The calculated velocities undergo testing at each time step to confirm adherence to the CFL condition. The initial time step in FDS is automatically determined based on the grid cell size divided by the characteristic flow velocity. Throughout the computation, the time step dynamically adjusts, constrained by the convective and diffusive transport speeds to uphold the CFL condition in every step. Eventually, as the fire attains a steady state, the time step is transitioned to a quasi-steady value, typically around 0.01 in all scenarios.

 (22)

At the same time, our previous study20 on smoke back-layering length and critical velocity in a metro train and horizontal tunnel was validated through comparisons of ventilation velocity and critical velocity with simulation models and small-scale experiments. In this study, a comparison between the simulation data and experimental results was conducted to further validate the reliability of the numerical model. An experimental comparison condition was conducted with a fire source heat release rate of 5.75kW, a slope of 2.29°, and a downstream length of 2.3m to the NS-3 in the numerical simulation, as illustrated in Fig. 8(b). The dimensionless distance 2x/*Ltrain* is used to represent the position of the measuring point, where xis the distance from the measure point to the fire source. A limited number of measurement points were selected to compare the trends in the variation of ceiling temperatures between the train and tunnel. The comparison demonstrated a high degree of agreement between the numerical and experimental outcomes, providing further validation for the reliability of the grid system employed in this study.



(a)



(b)

**Fig. 8.** Grid independence and model validation: (a) Grid independence verification, (b) Comparison of the smoke temperature profile between the simulation and experiments.

# 5. Simulation Results and Discussion

# 5.1 Prediction of the longitudinal induced airflow velocity

The Fig. 9(a) illustrates the induced airflow velocities at various tunnel slopes and downstream lengths from NS-1 to NS-35, with a fire source power of 5 MW. It can be seen that the induced air velocity increases linearly with the downstream length for each tunnel slope. This is because the enhanced stack effect with increasing tunnel slope and downstream length causes an acceleration of entraining fresh air into the tunnel. Simultaneously, the linear equation (*V*in = *k·L*down) of induced air velocity with the downstream length for each tunnel slope is fitted. The correlation coefficient of each line is greater than 0.97. This indicates a credible linear relationship between the longitudinal induced air velocity (*Vin*) and downstream length (*Ldown*), showing a significant positive correlation.



(a)



(b)

**Fig. 9.** Prediction of longitudinal induced airflow velocity: (a) Longitudinal induced velocity with different tunnel slopes and downstream length, (b)Correlation of line slope *k* and tunnel slope *α*.

To obtain the induced airflow velocity in relation to the tunnel slope and downstream length, it is necessary to determine the relationship between the line slope *k* and different tunnel slope *α*, as plotted in Fig. 8(b). As the fire heat release rate is unchanged in this work, the relationship between *V*in, *α* and *L*down can be determined by Eq. (23):

 (23)

The value of *Vin* in Eq. (23) is determined through numerical simulation measurements, with the governing equations described in Section 4.1 as part of the internal calculations of the software. *Vin* demonstrates a strong correlation with both the downstream length and tunnel slope (*R2*= 0.98). This correlation not only implies that the downstream length and tunnel slope influence the smoke back-layering length in inclined metro tunnels but also suggests the possibility of using these parameters to predict the back-layering length.

# 5.2. Smoke back-layering length for smoke gas front stopped in the train (*L* ≤ *L*f)

Based on the peak temperature position and smoke backflow front, the back-layering length can be determined. There are 25 scenarios in which the smoke back-layering length is less than the distance from the fire source to the front of the train and the tunnel slopes in these scenarios are in the range of 2.29°-4.57°. Fig. 10 shows the relationship between the smoke back-layering length *L* and fire location *L*down under 25 scenarios from NS-11 to NS-35. It can be seen that as the tunnel slope increases, the back-layering length becomes shorter. At the same time, the distance for smoke back-layering length decreases gradually with an increase in downstream length. However, it was found in several slope tunnels that the smoke spread to the front train and no longer overflow. The smoke back-layering length with the downstream length of 115m is the same in the tunnel slopes of 2.29°, 2.86° and 3.43° respectively. The reason is the competition between the thermal buoyancy of fire sources and the inertia forces induced by the stack effect. For the emergency evacuation door region, the area of the emergency evacuation door is small compared with the tunnel cross-sectional area, and the inertia force induced by the stack effect is relatively high. According to the simulation results, we deduced that this distance is about 20 m from the front train. As a further trend, the thermal buoyancy is greater than the inertia force and the smoke will overflow into the tunnel when the fire source is less than 20m away from the train front (115m<*Ldown*<135m). Among the three scenarios affected in the emergency evacuation door area, the one with a slope of 2.29° experiences the most significant impact. Referring to Fig. 10 and analyzing the trend of data points, we estimate that the backflow length under this scenario is approximately 7m. In the cases with slopes of 2.86° and 3.43°, the influence of the emergency evacuation door is comparatively minor, estimated to be around 2m. Considering that the influence of this change on the smoke back-layering length is small, they are fitted and analysed together with other conditions.



**Fig. 10.** Relationship between *L* and *L*down for smoke stopped in the train.

Modified Richardson number *Ri* is used to characterising the smoke back-layering length under the coupling effect of air entrainment and chimney effect driving acceleration. Fig. 11 shows the relationship between the normalized back-layering length *L*\* (*L* normalized by hydraulic train height *H*train) and the modified Richardson number under varying fire source location and tunnel slope. It is clearly shown that the smoke back-layering length increases with modified Richardson number and the simulation data can be correlated with a logarithmic function of modified Richardson number. The relatively low fitting correlation coefficient of *R*2 = 0.91 might be the result of the side door coupling effect. It is worth noting that the train ventilation velocity changes with the fire location in the longitudinal ventilation metro tunnel. However, the longitudinal-induced airflow velocity caused by the stack effect is small in this study. Therefore, all fire locations are fitted in Eq. (24), ignoring the change of the train ventilation velocity with the fire location.

 (24)

To take the tunnel slope and downstream length into account, the modified Richardson number *Ri* in Eq. (24) is replaced by Eq. (23). The modified non-dimensional smoke back-layering length can be expressed as Eq. (25):

 (25)

Eq. (25) indicates that the back-layering length will change with the downstream length and the tunnel slope when the smoke stopped in the train. As Eq. (25) was obtained under the condition of a train stopped in the tunnel with lateral side-door openings, it should be used with special care for ordinary inclined tunnel fires. According to Eq. (25), Taking *L* as *L*f we can derive the transition tunnel slope induced by train fire in an inclined double long-narrow space under natural ventilation.

 (26)



**Fig. 11.** Relationship between *L*/*H*train and *Ri*train for smoke stopped in the train.

# 5.3. Smoke back-layering length for smoke gas front stopped in the tunnel (*L* > *Lf*)

When the tunnel slope is small, the smoke gas will break through the train blockage region and spreads into the tunnel region, resulting in the smoke back-layering length greater than the distance from the fire source to the front of the train *L*st, just as analysed in Section 2.2. Simultaneously, the fire heat release rate of the virtual fire source can be obtained according to Eq. (11).

Utilizing numerical simulation results, the study observes that, across 10 scenarios (NS-1 to NS-10), encompassing tunnel slopes between 1.15° and 1.72°, the smoke gas front comes to a stop in the tunnel (*L* > *Lf*). Fig. 12 illustrates the dependence of the smoke back-layering length produced by the virtual fire source *L*u on downstream length *L*down under 10 scenarios from NS-1 to NS-10. It is necessary to note that the smoke back-layering length *L* in NS-8 is equal to the distance *L*f. It is analysed together with the other nine working conditions to ensure the continuity of the model. It was shown that, with *Ldown*=75m as the dividing point, as the downstream length increases, the smoke back-layering length first decreases and then increases. The smoke back-layering length generated by the virtual fire source reaches a minimum value with 75m downstream length. In the case of a 1.15° tunnel slope, the smoke back-layering length produced by the virtual fire source varies between 60m and 105m. Meanwhile, for a 1.72° tunnel slope, the smoke back-layering length from the virtual fire source fluctuates within the range of 0m to 60m. According to the modified Richard number in Eq. (12), it is found that the longitudinal induced airflow velocity is a determining factor in the decrease process of the slope. In the process of slope increases, the influence of the virtual fire source heat release rate becomes more obvious. Two variables affecting the smoke back-layering length *L*u reach equilibrium at a certain position in the middle of the train. This variation law is different from the model of the smoke back-layering length in an inclined tunnel in literature due to the change of smoke flow path sections in this study 23, 32.

\*-

**Fig. 12.** Relationship between *L*u and *L*down for smoke stopped in the tunnel.

Fig. 13 plots the dimensionless smoke back-layering length *L*u/*H*tunnel with modified Richardson number under varying fire source locations and tunnel slope. The results further demonstrate, as elaborated in Section 2.2, that the simulated data correlates with the logarithmic function of the modified Richardson number *Ri*. All the data can be correlated into a universal form with a correlation coefficient of 0.95:

 (27)

******

**Fig. 13.** Relationship between *L*u/*H*tunnel and *Ri*tunnel for smoke stopped in the tunnel.

Substituting Eq. (23) into Eq. (27), the dimensionless smoke back-layering length *L*u\* produced by the virtual fire source can be expressed as Eq. (28):

 (28)

By substituting Eq. (9) into Eq. (28), the final expression of the smoke back-layering length for smoke stopped in the tunnel is established as Eq. (29):

 (29)

To verify the accuracy of Eq. (29), numerical simulations with different fire heat release rates from NS-36 to NS-43 are carried out. Additionally, we compared the correlation with prediction model cited in the references 15, 23. Hu et al. conducted model experiments in longitudinally ventilated tunnels, employing effective heat release rates to obtain smoke back-layering length in the event of a metro carriage fire. While Hu's model considered the impact of a single side door, this study takes into account the influence of 24 side doors. Additionally, although Hu's model is designed for longitudinally ventilated tunnels, in this study, the longitudinal ventilation velocity can be replaced by induced airflow velocity. On the other hand, Kong et al. utilized numerical simulations and Richardson numbers to determine smoke back-layering length in the case of a fire in an inclined tunnel. Despite this study focusing on metro tunnels, the use of virtual fire sources allows us to disregard the impact of the train on smoke back-layering lengths concerning the situation where the smoke front stops in the tunnel. Therefore, the two models were selected for comparison to verify the applicability of the current results.

The predicted values are compared with experimental data and those literature data, as shown in Fig. 14. It is known that the experimental values demonstrate good agreement with the predicted values. The error between the predicted data and measurement data is less than 20%. The error in numerical simulations and experiments may stem from uncertainties in experimental measurements and the incomplete depiction of the intricacies inherent in the actual system. At the same time, this global correlation on smoke back-layering length caused by train carriage fires in an inclined metro tunnel can be further validated for its feasibility and applicability. The excellent agreement between the experimental data and the proposed correlation shows that the above analysis of the effect of downstream length, tunnel slope, cross-section change and carriage side-doors coupling effect on smoke back-layering length for smoke control in an inclined metro tunnel is reasonable. In contrast, tunnel slope and downstream length have more obvious effects on the smoke back-layering length.

Finally, the piecewise function relating the dimensionless smoke back-layering length, downstream length, and tunnel slope for carriage fires in the inclined tunnel under natural ventilation was obtained. In the event of a train carriage fire occurring in such an inclined tunnel, rescue personnel can effectively assess the smoke backflow length based on on-site conditions using Eq. (30), thereby formulating informed and practical rescue measures.

 (30)



**Fig. 14.** Comparison of dimensionless smoke back-layering length in the results from small scale model experiment, CFD simulation and Hu et al. model and Kong et al. model.

# 6. Limitations of the Study

This study has significant contribution to investigate the fire hazard induced by carriage fire in inclined metro tunnels under natural ventilation. However, there are some limitations in this study. Firstly, the study only considered a limited number of fire source locations and train positions, and the results may not be generalizable to other scenarios. Secondly, in a laboratory setting, the study did not consider the effect of environmental wind on smoke behavior in the tunnel, which could be an important factor in real-world situations of a subway tunnel fire.

# 7. Error and Uncertainty Analysis

The precision of experimental outcomes relies on the precision of the experimental apparatus. In a prior investigation40, it was determined that the uncertainty in calculated results could be accurately estimated using the root-sum-square (RSS) method. The fundamental equation is then formulated by amalgamating uncertainties from individual variables, and it is expressed as:

 (31)

where each term represents the contribution of one variable's uncertainty, *δXi*, to the overall uncertainty in the outcome, *δR*.

Following this, the measurement uncertainty in the present study can be estimated as follows.

(1) Uncertainty of the burning rate measurement.

Prior studies41, 42 have demonstrated the methodology to derive the relative uncertainty of the measured burning rate, , as follows:

(32)

where , and  are respectively represent the relative uncertainties of the measured mass loss, time interval of stable stage, and pool surface area. The measurement uncertainty in fuel quality is primarily influenced by the readability, linearity, and repeatability of the electronic balance. According to the technical guide, the relative error for all values is ±0.1g. Simultaneously, the uncertainty in the measurement time interval of the electronic balance is 0.5s, and the area of the fuel pans is determined with a ruler, introducing an uncertainty of 1mm. By substituting these values into Eq. (32), the maximum relative uncertainty of the burning rate in this study is calculated to be less than ±5%.

(2) Uncertainty of the temperature measurement.

During this study, all combustion tests were conducted at an ambient temperature of approximately 15 °C. K-type thermocouple, with a temperature reading uncertainty of ±0.1 °C, was employed for temperature measurements. Taking a conservative value of ±1 °C into account, the relative uncertainty of temperature is calculated as . Consequently, the maximum relative uncertainty in temperature measurement is estimated to be approximately ±3.7%.

(3) Uncertainty of the velocity measurement.

The average velocity of the measuring plane is determined by taking the arithmetic mean value of nine measuring points. The uncertainty of *0* can be calculated as follows 43:

 (33)

 (34)

where *ui,j* means the *j* th measured value of *ui*, and *n* is the number of measurements of the *i* th measuring point. The maximum uncertainty of the velocity in this study is 1.8 × 10-2, and the maximum uncertainty in Test 17 is ± 4.7%.

# 8. Conclusions

This study investigated the impact of double long-narrow spaces on smoke back-layering induced by carriage fires in an inclined tunnel under natural ventilation. This study considered the effect of cross-sectional change, downstream length, tunnel slope, and side-door coupling on the smoke back-layering length. The main findings of this study are as follows:

* The model experimental results suggest that the impact of the heat release rate on the smoke back-layering length is relatively minor. From an engineering standpoint, it is acceptable to disregard the influence of the heat release rate on the smoke back-layering length.
* For situations where the smoke gas front stopped in the train, the slope of the tunnel has no significant effect on the smoke back-layering length when the fire location is about 20 m from the train head and the tunnel slope is in the range of 2.29° to 3.43° for smoke gathered in the stopped train with the side door opened.
* For situations where the smoke gas front stopped in the train, there is a negative correlation between the downstream length and tunnel slope and the back-layering length. Meanwhile, there is a linear positive correlation with the induced airflow velocity. The influence of side door coupling on the back-layering length can be disregarded due to the low induced airflow velocity (*Vin-max*=0.9m/s), and a fitting result of *R*2 = 0.91 is obtained.
* For situations where the smoke gas front stopped in the tunnel, at slopes below 1.72°, smoke spills from the carriage and spreads within the tunnel. As the downstream distance increases, with *Ldown*=75m as the dividing point, the smoke back-layering length produced by the virtual fire source initially decreases, then increases due to changes in the smoke flow path sections of the special double long-narrow structure.
* A dimensional correlation of the transition slope induced by carriage fire in an inclined tunnel under natural ventilation was proposed. The correlation indicates that the *L\** is a piecewise function with a transition slope as the dividing point, and prediction results have an error of within 20% compared to the experimental data (Eq. (30)). The errors in this part may arise from potential inaccuracies in controlling conditions such as temperature, humidity, and pressure during the experiment, which can affect the accuracy of the experimental results.

In terms of future research, there are several areas that should be considered. Firstly, the effect of the train's ventilation system, air conditioning system, emergency ventilation system, and fire suppression system on smoke behavior characteristics in a carriage fire in an inclined metro tunnel should be investigated. Secondly, more fire sources and train locations should be considered to research the specific influence of the blocking effect at the emergency evacuation door on smoke behavior characteristics. Lastly, future studies should consider the effect of wind on smoke behavior in the tunnel to better replicate real-world conditions.

### Conflict of interest

There is no conflict of interest.

### Funding

This work was supported by the Beijing Natural Science Foundation (Grant No: 8172006), the Natural Science Foundation of China (Grant No: 51378040), the National Natural Science Foundation of China (NSFC) [Grant No. 52104185] and the Research Foundation of Chongqing for graduated doctor [Grant No. CSTB2022BSXM-JCX0151]. We sincerely appreciate this support.

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