Analysis on ventilation pressure of fire area in longitudinal ventilation of underground tunnel

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Abstract. In order to solve the problem of ventilation pressure loss in the fire area under the fire condition, the wind pressure loss model of the fire area is established based on the thermodynamic equilibrium relation. The semi-empirical calculation formula is obtained by using the model experiment and CFD simulation. The validity of the formula is verified. The results show that the ventilation pressure loss in the fire zone is proportional to the convective heat release rate at the critical velocity, which is inversely proportional to the upstream ventilation velocity and the tunnel cross-sectional area. The proposed formula is consistent with the law of the tunnel fire test fitting formula that results are close, in contrast, the advantage lies in a clear theoretical basis and ventilation velocity values. The resistance of road tunnel ventilation system is calculated accurately and reliably, and then an effective emergency ventilation operation program is developed. It is necessary to consider the fire zone ventilation pressure loss. The proposed ventilation pressure loss formula can be used for design calculation after thorough verification.

1. Introduction

When a fire occurs in the tunnel, the heat release of the fire source, the expansion of the flow of the air flow and the expansion of the viscosity result in additional ventilation pressure loss (also known as fire zone resistance). When the tunnel downstream has a certain slope, there will be fire pressure. In the current domestic design specifications for highway tunnels (mainly to the mountain tunnel), the fire conditions under the ventilation resistance calculation considered the fire pressure, ignoring the fire area ventilation pressure loss. Urban underground roads and mountain road tunnels compared to the tunnel structure and external wind environment are different. The vertical plane of the underground road is generally concave, mainly in straight sections, and the effects of natural winds and fire pressure are not as large as those of highway tunnels. At this point the fire zone ventilation pressure loss which has become an important factor in the ventilation system resistance calculation should be taken into account.

Analysis of ventilation pressure loss in the fire area is the first to originate from the roadway fire. Calvin K. Lee et al. [1] tested the magnitude of the pressure difference before and after the fire zone in the well model. Zhou [2] and Cheng [3] draw the ground tunnel fire resistance research ideas, and put forward the horizontal tunnel fire resistance formula. Zhou's fire resistance concept includes the acceleration of the fire zone and the fire zone downstream frictional resistance. However, the analysis

of Zhou didn't properly consider the thermodynamic equilibrium relationship of the fire area, and can't calculate the static pressure loss directly from the dynamic pressure change before and after the fire in the fire area. Cheng's fire zone resistance concept by the flow of fuel resistance, flow resistance in the fire when the increase in the fire and the heat generated by the three parts, the fire resistance and the scale of fire in a linear relationship, with the fire zone entrance ventilation velocity has a quadratic curve relationship, the ventilation velocity didn't affect the heat release rate conditions, the additional ventilation resistance was proportional to the fire zone inlet ventilation velocity. This was not consistent with the results obtained by the highway tunnel model test conducted by Wang et al. [4]. In the case of the same scale of fire, the total pressure difference between the upstream and downstream of the fire zone decreased with the increase of ventilation velocity. This indicated that there were problems in the conclusion that Cheng's analysis of the uniform pipe flow before and after the fire zone. R Dutrieue[5] used Fluent software with volume heat source, conducting a large number of numerical simulation after fitting to get a tunnel fire pressure loss formula. When fire resistance and frictional resistance merged, volume heat source didn't accurately reflect the complex combustion process. The French Tunnel Research Center gave an experimental formula, but didn't provide experimental data sources and lack corresponding theoretical analysis.

   In summary, we can see that there is no theoretical basis but also to meet the engineering needs of the fire zone ventilation pressure loss formula. Based on the analysis of the thermodynamic equilibrium relationship of the fire zone, this paper proposes a formula for the ventilation pressure loss under the critical wind speed. The formula only calculates the resistance of the fire zone, not including the downstream frictional resistance, and verified by the model experiment and numerical simulation verification.

2. Theoretical analysis of ventilation pressure loss in fire area

2.1. Theoretical formula derivation

Considering the critical scale of the fire scale and the parameters of the tunnel structure, the ventilation resistance calculation is concerned with the case where the upstream wind speed is about the critical wind speed. As shown in Figure 1, the upstream of the fire area is a uniform flow. When the upstream air flows through the fire zone, on the one hand, the air flow thermal expansion in fire plume flow generating the local pressure at the upstream side of the wind direction with the opposite side, on the other hand, the air flow in the buoyancy and turbulent mixing process of viscous diffusion are the dominant factors of fire zone wind pressure loss. In addition, the downstream side of the fire area for the stratified flow, the upper hot flue gas and lower air mixing, while convection and radiation to the tunnel wall heat transfer. And the lower air near the fire area is affected by the lifting action of the plume, offsetting the expansion of the hot flue gas on the downstream side. In short, the downstream side of the laminar flow has additional effective driving force to the full range of air flow.
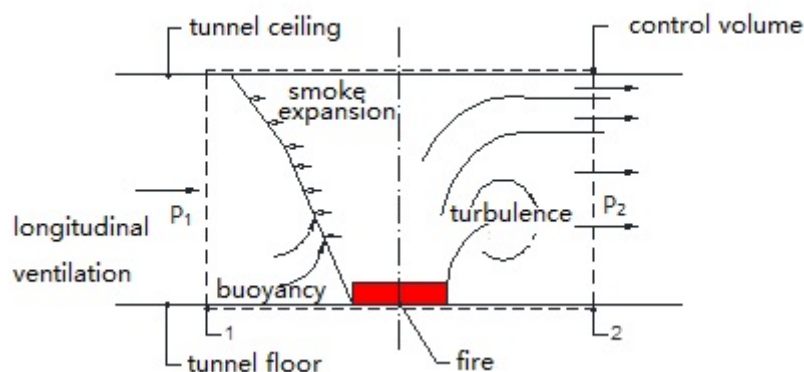

Fig 1. Control volume for pressure loss through fire zone

The fire area between the tunnel section 1 and section 2 in Fig. 1 is taken as a control body. P1 is the static pressure before the airflow enters the fire zone, P2 is the static pressure of the lower airflow in the fire zone, and the wind pressure loss in the fire area is:

$$\Delta p = p_1 - p_2 \qquad (1)$$

ΔP is generated by the combustion of smoke and the source of the air into the thermal expansion and viscous diffusion. From the perspective of thermodynamic macroscopic energy balance, it is assumed that when the fire plume flow pattern is similar, the wind static pressure loss is equal to a certain percentage of the fire source convection release heat per unit time (denoted $\alpha\dot{Q}$, $\dot{Q}$ as the total heat release rate, $\dot{Q}_c$ for convective heat release Rate, $\dot{Q}_c \approx 0.67\dot{Q}$) the negative work done by the wind, there is:

$$\Delta p \cdot \Delta V = \alpha\dot{Q} \qquad (2)$$
$$\Delta V = V_{air} + V_{smoke} \qquad (3)$$

Where ΔV is the amount of gas entering the fire zone per unit of time. A large number of studies have shown that the flue gas produced by combustion pyrolysis V_{smoke} is much smaller than the amount of air flowing into and out of the upstream V_{air}, Therefore

$$\Delta V \approx V_{air} = Av \qquad (4)$$

Where A is the tunnel cross-sectional area at the fire source and the average wind speed for the tunnel section upstream of the fire zone. Fire zone wind pressure loss

$$\Delta p = \frac{\alpha\dot{Q}_c}{\Delta V} \approx \frac{\alpha\dot{Q}_c}{Av} \qquad (5)$$

Equation (5) shows that when $v \approx v_c$, the wind pressure loss is ΔP proportional to the convective heat release rate $\dot{Q}_c$ and is inversely proportional to the wind speed v and the area A in the upper zone. When $v < v_c$ or $v > v_c$, the change trend does not change, and Wang made by the road tunnel fire model test results are consistent, but the fire plume flow pattern is no longer similar, and there is no longer a linear relationship between wind pressure loss and its influencing factors.

2.2. *Determination of empirical constants*

By analyzing the experimental results of the French Tunnel Research Center (CETU), the wind speed is in the range of 1.5-3.5m/s, and the approximate formula [6] is following:

$$\Delta p = c \times \frac{\dot{Q}_c}{v_0 D_r^2} \qquad (6)$$

Where $\dot{Q}_c$ is the convective heat release rate of the fire source, and its value is 2/3 of the total heat release rate, $c \approx 9 \times 10^{-5}$, D_r is the hydraulic diameter, and v_0 is the initial wind speed in the tunnel. Referring to the formula (5), and comparing the values of the typical tunnel cross-sectional area and the square of the hydraulic diameter in Table 1, $\alpha \approx 8 \times 10^{-5}$ can be obtained, which also means that when the flow pattern is similar, α assumed to be a constant is reasonable.
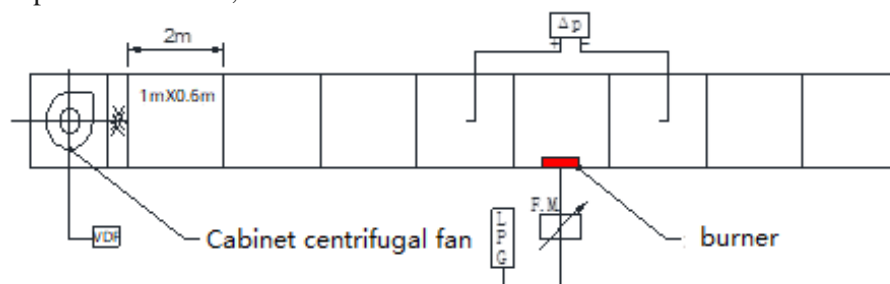

Fig 2 Layout of experimental tunnel model for measuring ventilation pressure loss through fire

Table 1. Comparison of cross-sectional area and hydraulic diameter squared for typical tunnels

Section form	A/m^2	D_r/m	D_r^2 /m^2	D_r^2/A /m^2
T5.5	28.77	5.6	31.36	1.09
T7	37.23	6.5	42.25	1.13
T8.5	49.66	7.4	54.76	1.10
T9.5	53.53	7.6	57.76	1.07
T11.5	70.89	8.7	75.69	1.06
T12.5	75.41	8.8	77.44	1.02

Table 2. Test data of model experiments

case	$\dot{Q}_c/kW$	$Q/m3\cdot h^{-1}$	$v/m\cdot s^{-1}$	Measured $\Delta p/Pa$	Prototype tunnel's $\Delta p/Pa$	Calculated $\Delta p/Pa$
5MW	18.9	1560	0.69	0.16-0.20	1.28-1.60	3.44
10MW	37.8	2000	0.88	0.44-0.46	3.52-3.68	5.38

3. Verification of ventilation pressure loss formula in fire area

In formula (5), the relationship between the wind pressure loss and the critical wind speed is not considered. In order to further verify the validity and accuracy of the formula (3), the model experiment test and CFD numerical simulation are carried out respectively.

3.1. Model test of wind pressure loss in fire area

In the 1: 8 scale model, the TSI DP-CALC Model 8710 micro barometer (accuracy 0.01Pa) was used to test the differential pressure variation before and after the fire zone and the corresponding critical wind speed.

A schematic diagram of experimental layout is shown in Figure 2, the longitudinal wind speed is provided by the cabinet centrifugal fan connected to the left end of the model, and the wind speed is changed by adjusting the frequency converter (VDF). The fire source system consists of a gas tank, a pressure reducing valve, a flowmeter (F.M.) and a burner, and liquefied petroleum gas (LPG) is used as fuel to simulate the different sources of fire by adjusting the gas flow. The heat release rate of the gas source is determined by:

$$\dot{Q} = \eta \dot{m}_f H_c \tag{7}$$

Which, η is the combustion efficiency of the gas, taking 94.0%, $\dot{m}_f$ is the mass flow rate of the gas. Liquefied petroleum gas under normal pressure density taking 2.35 kg/m^3, combustion heat value H_c taking 46.15 MJ/kg.

Comparison of the two kinds of conditions in Table 2 under the pressure difference data can be found in the case of little change in wind speed, the fire power doubled, the fire before and after the pressure difference is also increased by about twice, which is consistent to the formula (3) of the relationship between the pressure and the fire power. But converted to the prototype tunnel, conversion values are much lower than the formula calculated value, of which 5MW and 10MW conditions, the test conversion value of the highest value of the formula were 47% and 68%, this situation is due to romantic and fire flow interacts, the similarity relationship given by NFPA92B[7] does not apply to the conversion of wind flow parameters. The prototype CFD simulation will be used to compensate for the shortcomings of the model experiment.

3.2. Simulation of wind pressure loss in fire area by CFD method

The widely validated fire dynamics simulation software FDS6 [8-9] has been used to simulate the pressure difference between the fire zone before and after the fire scale and the corresponding critical

wind speed on the two-lane underground road (8m×5m cross section), the main simulation parameters are shown in Table 3. Calculating the critical wind speed uses Y. Wu's formula [10]. As shown in Fig. 3, the calculation results of equation (3) are very close to the simulation results in the fire range of urban underground roads (5-30MW). CFD simulation has been used to verify the accuracy of the formula (3) in the conventional two-lane underground road.

Table 3. Input parameters in FDS

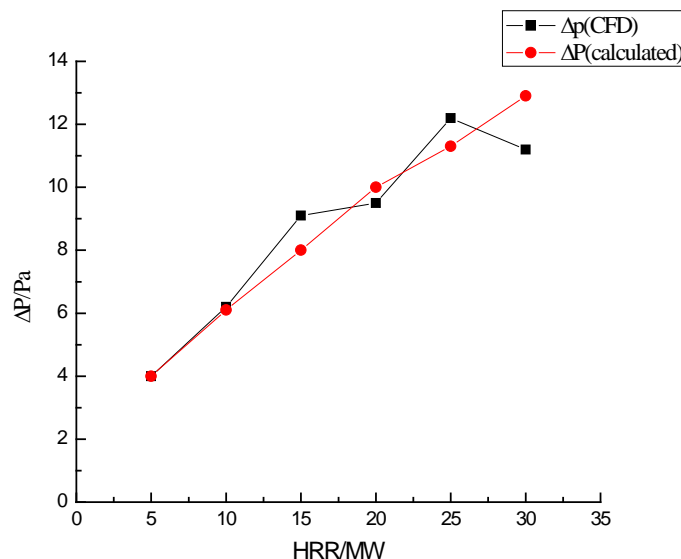| parameter	value or attribute
Model length	40m
Grid size	0.4m×0.2m×0.2m
Boundary conditions	Supply (Entrance) , Open (Export)
Fire source location	X: 20m – 25m
Fire source size	5m×2m (5MW, 10MW)
	5m×3m(15MW); 5m×4m(20MW)
	5m×5m(25MW); 5m×6m(30MW)
measurement points	X1:15m; X2:30m, Y:4m, Z:2m

Fig 3. Comparison of the results of CFD and the formula

4. Conclusion

1) Based on the stratified flow in the downstream of the fire zone, the calculation formula of the wind pressure loss in the fire zone associated with the critical wind speed is obtained by applying the thermodynamic equilibrium relationship.

2) The numerical simulation proves the accuracy of the application of the wind pressure loss formula in the two - lane underground road, and the applicability of the tunnel width and blocking is still to be tested.

3) The calculation results of the wind pressure loss formula in the fire zone are input into the one-dimensional model of the tunnel ventilation. The results show that taking the fire zone wind pressure loss into consideration to obtain accurate air flow parameters in the calculation of ventilation resistance.

Acknowledgments

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