Influences of Fire Curtain on Smoke Exhaust Effect of Longitudinal Ventilation and Shaft Smoke Exhaust Combination Mode

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Abstract: The aim of this study is to investigate the Influence of fire curtain on smoke exhaust effect of longitudinal ventilation and shaft smoke exhaust combination mode, combined with the actual project established a scale physical model of 1:3, and analyzed the smoke exhaust effect of longitudinal ventilation and vertical shaft smoke exhaust combination mode, measured the fire heat release rate, smoke spread, the temperature inside the tunnel. The results show that the tunnel fire, longitudinal ventilation and shaft smoke exhaust combination mode has a certain effect to control of flue gas, open fire curtain, the flue gas is controlled to a certain range, there is conducive to better gas discharge tunnel, can provide protection for traffic safety.

1. Introduction

With the continuous growth of China's economy, the number of domestic tunnels is increasing, and the security problems in tunnels will face severe challenges. Study on tunnel fire is an urgent need for traffic safety in China at present, which can provide protection for the safety of the transportation tunnel, improve transportation safety and promote the economic development.

Because of the tunnel sealing and the difficulty of evacuation and rescue, once the tunnel fires, it will cause serious disaster. Blanc peak tunnel fire occurred in March 24, 1999, causing huge economic losses. According to the fire investigation, the Blanc peak tunnel fire is the erroneous ventilation and smoke exhaust patterns that exacerbate the combustion. Many scholars have done a lot of research on the control of flue gas. Feng Liang [1] has studied longitudinal ventilation and Shaft Smoke Exhaust, the research shows that when the fire occurs in the central area of the tunnel, the upstream jet fan longitudinal ventilation and shaft smoke extraction should be adopted. Liu Yang [2] studied the influence of vertical shaft on natural smoke exhaust of highway tunnel, and gave a reasonable way of smoke exhaust. Yi Lei [3] has studied the smoke prevention characteristics of smoke proof Curtain. The results show that the smoke proof curtain has good smoke resistance and heat resistance. At present, there is little research on fire shutter, based on the actual tunnel engineering; the author builds a scale model of 1:3, to explore the effectiveness of rolling smoke exhaust system.

2. Backgrounds

2.1 Tunnel Structure
A tunnel is a highway tunnel. Main tunnel is two-way six lanes and can provide sectional wind speed of 5m/s, the design speed is 60km/h, there is a partition wall in the middle, whose width is 13.05m, and height is 6 m. The loop tunnel is a two-way two lane, with a design speed of 20 km / h, loop tunnel width is 12.45m, height is 5.2m. This experiment assumes that fire occurs at the center of loop tunnel, and explores the control effect of smoke. According to the study results of Liu yuan, the longitudinal ventilation loop tunnel should be set to 3m/s.

![Fig. 1 Tunnel Prototype](image)

2.2 Determination of Heat Release Rate of Fire Source
The heat release rate (HRR) of different types of automobile fires is shown in table 1. In this experiment, the fire heat release rate is 20~30MW. [4]

| Models       | Minibus | Large Bus | Van | Public Transport | Truck |
|--------------|---------|-----------|-----|------------------|-------|
| HRR/MW       | 2.5     | 5         | 15  | 20               | 20~30 |

3. Models

3.1 Similarity Criterion
In order to study the effect of smoke control, the author uses scale model to test. Scale model tests need to ensure that the smoke flow of model and prototype meets the similar conditions, including geometric similarity, kinematic similarity, dynamic similarity, initial condition similarity and boundary condition similarity. Based on the differential equation of smoke flow, a model is established by using the similarity transformation method, that is, the Froude fire model. According to the actual situation, the model ratio is 1:3, and the scale model test platform is established. The similar scales of each parameter are shown in Table 2.

| main parameter | Geometry dimension (m) | Geometry dimension of loop tunnel(m) | speed of main tunnel(m/s) | HRR(MW) |
|----------------|------------------------|-------------------------------------|--------------------------|---------|
| similarity criterion | 1:3                   | 1:1.732                            | 1:1.732                  | 1:15.576 |
| test model     | 4.35×2(main tunnel)    | 2.3                                | 1.7                      | 1.28~1.93 |
|                | 4.15×1.73(looptunnel)  |                                     |                          |         |

3.2 Model Experimental Platform
According to tunnel engineering practice and similarity criterion, a tunnel scale test platform with longitudinal ventilation and shaft smoke extraction system is established. The length of the main
tunnel is 90m. According to the previous research results, decided to set up the fire shutter to the exit of the loop tunnel, and the specific size is shown in Figure 2.

Fig. 2 Models Experimental Platform

3.3 Test Bench Layout
The number of thermocouples arranged on the tunnel is 50, used to measure tunnel temperature changes. The location is shown in Figure 3; T is the abbreviation of thermocouple. TS is the abbreviation of thermocouple string, the distance between thermocouple arrangement is 10m, the distance between thermocouple strings is 20m, and two thermocouple strings are arranged on both sides of fire source. The tunnel is equipped with 10 cameras, used to observe the spread of smoke. Three radiant heat flow meters are arranged on both sides of the fire source for measuring the radiant heat of the fire source and the distance from the fire source is 3m. The electronic scales are placed below the fire source to measure the mass change of the combustion material.

Fig.3 Test Bench Layout
4. Experimental Results Analysis

This experiment uses tires as combustion materials to explore the law of smoke flow.

4.1 Longitudinal Ventilation and Shaft Smoke Exhaust Combination Mode (No fire shutter)

4.1.1 Experimental Phenomena

(1) The experimental phenomenon of camera observation

Through the camera, we can see that in the early stage of the experiment, the smoke spread downstream, no smoke backflow occurred, the smoke was basically controlled, the flame height was 0.8m at 48S. Because the tunnel is a loop tunnel, at 5 minutes, smoke from the other side into the tunnel, the tunnel flue gas increased. As the fire power decreases, the flame height decreased. The experiment ended in 40 minutes.

(2) Experimental phenomena before and Behind shaft

You can see from Figure 5, Figure 6 that the shaft smoke exhaust has a certain effect. The smoke in the tunnel is continuously discharged from the shaft, a small amount of smoke enters the main tunnel, and the flue gas entering the main tunnel is stratified. In the 9 minute, the main tunnel was filled with a great deal of smoke, creating a great deal of time for the evacuation of the people.
4.1.2 Heat Release Rate of Fire Source

In this experiment, the heat release rate of fire source is measured in two ways. One is heat loss method; the other is radiation heat flow meter method.

\[ Q = \frac{4\pi R^2 I}{X_r} \]  \hspace{1cm} (1)

In the formula, \( I \) is the target to receive radiant heat flow, \( \text{kw/m}^2 \); \( Q \) is the heat release rate of fire source, \( \text{kw} \); \( R \) is the radiation distance from the edge of the target to the flame center, \( \text{m} \); \( X_r \) is the total radiation score, taking 0.7.

\[ Q = \phi \times \dot{m} \times \Delta H \]  \hspace{1cm} (2)

In the formula, \( \phi \) is a combustion efficiency factor, and the value of \( \phi \) can be between 0.3 and 0.9; \( \dot{m} \) is the mass loss rate; \( \Delta H \) is the calorific value of the fuel.

\[ Q = \alpha \times t^2 \]  \hspace{1cm} (3)

In the formula, \( \alpha \) is the rate of fire increase, \( \text{kw/s}^2 \); \( t \) is the time to arrive at 1MW,s.
According to the change of tire quality, the mass loss rate of the tire can be calculated, and then the heat release rate of the tire combustion is calculated by formula 2, as shown in Figure 7. From the change curve of heat release rate, it is found that a short peak value occurs at the beginning of combustion, mainly due to the burning of the gasoline used in the ignition. With the combustion process, the tire is ignited, the heat release rate increases, reaching 1MW in 110 seconds, fire growth factor (formula3) was 0.0826kW/s², at 2 minutes, the end of the rapid growth, At 5 minutes, all the fuel surfaces are ignited, and the heat release rate reaches the maximum. The heat release rate began to decrease in 9 minutes when the fuel was not sufficiently strong to sustain combustion. At 40 minutes test collection is finished.

According to the data measured by the radiation heat flow meter, the heat release rate of the tire can be calculated by taking the formula 1. The heat release rate curve is shown in Figure 7. According to the heat release rate of the image, in the early stage of combustion, heat release rate increases gradually. No. 1 point reaches 1MW at 5 minutes, which reaches the maximum value of 1.67MW at 13 minutes. The No.2 measuring point reaches 1MW at 5 minutes, which reaches the maximum value 1.46MW at 8 minutes. No. 3 is smaller than the other two points, which reaches the maximum value 0.6MW. From this we can see that the heat radiation of upstream fire is smaller than downstream, because the longitudinal ventilation destroyed the flame plume, caused thermal radiation value is smaller.

4.1.3 Temperature

Fig.8 Temperature Variation (3m)
As shown in Figure 8, the temperature downstream of the fire is higher than that at the upstream of the fire. The temperature in the upstream of the fire has little change, and the maximum temperature is only 48℃. The temperature of 9-1, 9-2 and 9-3 is basically the same; the peak value is about 285℃, and the temperature of 9-4 is the lowest. It can be seen that the safety of the upstream of the fire is greater than that of the downstream, and the personnel flee as close as possible to the ground.

It can be seen from the Figure 9 in the tunnel flue gas temperature with the increase of the distance, the temperature is gradually decreasing. The highest temperature of T10 is 287℃, the highest temperature of T9 is 150℃, the highest temperature of T13 is 96℃, and the highest temperature of T2 is 67℃. The remaining thermocouples had little change in temperature.

![Temperature Variation at Ceiling (Distance to Fire Source)](image)

**Fig.9** Temperature Variation at Ceiling (Distance to Fire Source)

### 4.2 Open Fire Shutter

#### 4.2.1 Experimental Phenomena

1. The experimental phenomenon of camera observation

   - **0’00’’ Ignition**
   - **3’10’’** The thickness of gas layer is 0.2m
   - **4’15’’** The thickness of gas layer is 0.6m
   - **5’15’’** The thickness of gas layer is 0.4m
   - **6’20’’** The thickness of gas layer is 0.4m
   - **12’25’’** The thickness of gas layer is 1.2m
The thickness of gas layer is 1m

The thickness of gas layer is 0.6m

End test collection

Fig. 10 Experimental phenomena observed by camera

Through the experimental phenomenon, we can see that under this condition, the stratification phenomenon of smoke is obvious in the whole experiment. When the amount of smoke in the shaft is 6.9m3/s, after the fire shutter was closed, the fluidity of the flue gas becomes worse, and the Flue gas reflow phenomenon occurs at 3 minutes. In order to control the Flue gas reflux in tunnel, it is necessary to increase the wind velocity in the tunnel section. This experiment improved the smoke exhaust in the shaft to increase the wind velocity in the tunnel and promote the smoke flow in the tunnel.

At 5 minutes, the amount of smoke in shaft was increased to 9.8m3/s, the smoke reflux phenomenon was preliminarily controlled, but with the increase of ignition power, Flue gas reflux distance was greater than 5m. In 12 minutes, the smoke exhaust volume increased to 12m3/s, and after the shaft exhaust smoke increased, the smoke was controlled, 45 minutes combustion basically ended.

(2) Experimental phenomena observed by CM2

Ignition

small amount of smoke

The thickness of gas layer is 0.4m

The thickness of gas layer is 1.2m

The thickness of gas layer is 1m

End test collection

Fig. 11 Experimental Phenomena Observed by CM2

It can be seen from the images that after the test, the stratification of the smoke layer was more obvious, and the smoke in the tunnel began to increase at 2 minutes. At 12 minutes, the maximum amount of smoke was produced, the smoke layer in the tunnel reached the maximum 1.25m, and at 17 minutes, the smoke layer thickness began to decrease to 1m, at 45 minutes, end of the test.

(3) Experimental phenomena observed by CM10
It can be seen from the images that when the fire curtain is closed, the smoke is controlled in the loop tunnel and cannot spread to the main tunnel. At the beginning of the experiment, the smoke in the tunnel was stratified. At the beginning of the experiment, the smoke in the tunnel is stratified. In 4 minutes, the thickness of the flue gas layer is 0.9m, and in 12 minutes, because of excessive production of smoke, the flue gas in the tunnel cannot be immediately discharged, the flue gas accumulation, at 29min, the amount of flue gas began to gradually decrease, 46 minutes at the end of the test. Therefore, when the fire occurs, the temperature near the fire source is higher, should be far away from the fire source.

4.2.2 The Heat Release Rate of Tire

The method of data processing in this experiment is the same as 4.1.2. The Figure 13 shows that the curve trend of heat release rate is basically the same as 3.1, after the tire was ignited, the heat release rate increased first and then decreased, reaching 1MW at 448 seconds, fire growth factor was 0.0826kW/s², At 12 minutes, all the fuel surfaces was ignited, and the heat release rate reaches the maximum1.59 MW. The heat release rate began to decrease at 15 minutes when the fuel was not sufficiently strong to sustain combustion At 40 minutes test collection is finished.

According to the heat release rate of the image, The No. 1 point reaches 1MW at 582 seconds minutes, which reaches the maximum value of 1.65MW at 13 minutes. The No.2 measuring point
reaches 1MW at 582 seconds, which reaches the maximum value 1.99MW at 13 minutes. No. 3 is smaller than the other two points, which reaches the maximum value 0.8MW.

From the above we can see that the value of measured by the radiation heat flow meter in this experiment is larger than that measured by the electronic scale. The reason for the analysis is that the distance between the radiant heat flux and the fire source is smaller than 3m due to the flame tilting downstream. This experiment is based on the electronic scale measurement value. The fire growth coefficient of 4.2.1 and 4.2.1 shows that the fire speed is reduced after the fire shutter is opened, and it is helpful for people to escape.

4.2.3 Temperature

As shown in Figure 14, the downstream temperature is less than the upstream temperature. The upstream temperature is less than the upstream temperature. From the upstream thermocouple changes, it can be seen that the flue gas reflux phenomenon occurs. With the increase of the exhaust gas volume, the flue gas backflow is controlled. Because the 2 thermocouples are damaged during the experiment, 3 thermocouples are left in each thermocouple string. The peak value of thermocouple 8-1 is 197°C, and the 8-2 thermocouple reaches the peak value of 124°C. The peak value of 9-1 thermocouple is 439°C, the peak value of 9-3 thermocouple is 130°C, and the peak value of 9-4 thermocouple is 61°C. Therefore, when the fire occurs, the temperature near the fire source is higher, should be far away from the fire source.

Figure 15 shows the temperature changes at different locations in the tunnel. From the diagram, with the increase of time, the temperature firstly increases and then decreases, and after the ignition, the temperature rises rapidly because of the ignition of gasoline. When the tire is ignited, the thermocouple from the fire source 13m reaches its maximum value of 171°C in 14 minutes. The thermocouple from the fire source 23m reaches its maximum value of 143°C in 14 minutes, and the temperature was 28°C lower than 13m. The thermocouple from the fire source 31m reaches its maximum value of 143°C in 14 minutes, and the temperature was 14°C lower than 23m. It can be seen that the flue gas decreases rapidly with the increase of distance because the flue gas continuously exchanges heat with the air.
5. Conclusions
The experimental results show that the heat release rate of the fire is 1.87MW when the longitudinal ventilation speed is 1.7m/s, and the smoke exhaust rate is 6.9m$^3$/s, no backflow occurs in the flue gas. After opening the fire shutter, part of the flue gas backflow, need to increase the amount of shaft smoke exhaust, when the exhaust volume is 12.2m$^3$/s, smoke can be well controlled.

From the change of temperature, the temperature decreases with the increase of the distance between the fire source and the fire source. At the distance from the fire source 13m, the maximum temperature is 263 degrees. The temperature of the smoke outlet should not be greater than 280 degrees according to the specification. Therefore, it is suggested that the distance from the fire source location of the shaft smoke exit is not less than 13m.

For loop tunnel fire, longitudinal ventilation and exhaust shaft has a smoke effect, but part of the flue gas through the main tunnel, exit loop back to the fire place, and the main loop tunnel formed smoke loop, increase fire shutter smoke is controlled in a certain range, the flue gas is discharged from the shaft, the control effect is good for gas.

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