A review on Highway Tunnel Fire Test Research

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Abstract. The emergence of highway tunnels provides convenient conditions for transportation, but at the same time, many potential risk factors will restrict their normal use. Fire is the most common of these factors, so the danger of fire accidents cannot be ignored. This article briefly describes the characteristics and harmfulness of tunnel fires, reviews the current research status of highway tunnel fires, and summarizes the progress of highway tunnel fire experiments around the research methods, fire field characteristics, and ventilation control methods. Key factors including heat release rate, ceiling temperature, smoke stratification characteristics, multiple fire sources and the critical velocity were referred to in this article. The work could provide theoretical and technical support for the fire safety and smoke control design of highway tunnels.

Keywords.fire; highway tunnels; ventilation control; review

1.Introduction

With the continuous development of economic levels and improvement of people's requirements for quality of life, the scale and quantity of transportation tunnel construction have shown a continuous growth trend in China. In the light of the statistics of the Ministry of Transport in 2022, the total length of highway tunnels in China reached 24698900 linear meters, with a total number of 23268. On the other hand, with the continuous growth of traffic volume and the increase of driving speed and density, coupled with the special structure and environmental conditions of extra-long tunnels, traffic accidents and fires are easily caused in tunnels. Tunnel fires are always accompanied by high temperatures, suffocation, and poor visibility, making it hard for internal and external rescue efforts to reach the scene in a short period of time. A study by the United Nations Economic and Social Council pointed out that vehicle collisions and fires are one of the main factors causing tunnel fires, with 12 out of the 14 largest fire accidents in the world caused by this factor [1]. Relatively speaking, the tunnel section has a narrow field of view and poor visibility, making it an accident prone section. Once an accident occurs, it is highly likely to lead to a fire. In addition, defects in electrical systems, engine overheating, or other causes of spontaneous combustion of cars or loaded goods, as well as human factors such as arson, smoking, and terrorism, can also cause tunnel fires.

Several tunnel fires that occurred abroad have proven this result, such as the Mont Blanc tunnel fire in March 1999, which resulted in 39 deaths, the Tauern Motorway tunnel fire in May 1999, which resulted in 12 deaths, and the St. Gotthard tunnel fire in October 2001, which resulted in 11 deaths. Due to multiple similar tragedies in recent years, the prevention and control of tunnel

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fires has become a new research hotspot. This article provides a brief introduction to the basic situation and current research status of highway tunnel fires.

2.Research Methods For Highway Tunnel Fire

There are three methods commonly used in highway tunnel fire ventilation research: small-scale model test method, full-scale experiment through actual tunnel engineering, and numerical simulation using computational fluid dynamics to obtain the distribution of wind speed field, pressure field, and temperature field in the tunnel.

2.1.Small-scale model experiments

The study of simulated size experiments based on dimensionless fitting is a very important method for fire science research. Due to the complex cross-sectional shapes and huge aspect ratio of highway tunnel, it is difficult to construct full-scale or large-sized test platforms. Small scale simulation experiments are particularly important and widely used in research methods for highway tunnel fires.

In 1986, Hwang and Wargo conducted a study about the effect of tunnel slope on smoke diffusion. Subsequently, Atkinson and Wu conducted targeted research on the relationship between tunnel slope and critical velocity, and established a prediction model for critical velocity by the change of tunnel slope. In 1995, Oka obtained a critical velocity prediction model through small-scale model experimental research. In 2000, Wu and Bakar conducted experiments with a small-scale tunnel platform to research the critical velocity and corrected the Froude number in the prediction model. In 2002, Vauquelin and Mégret conducted an 1:20 scale model experimental study on tunnel ceiling smoke exhaust and obtained corresponding data parameters. In 2003, Kurioka analyzed the flame inclination angle of tunnel fires under longitudinal ventilation and then established a prediction model. In 2006, Vauquelin conducted an experimental study on the relationship between the critical velocity of tunnel fires and the width of the tunnel[2]. In 2008, Jae studied the effect of airflow velocity on the combustion rate of oil pool fires on a small-scale tunnel experimental platform. In recent years, small-scale model experimental methods have been widely used in the design of smoke exhaust modes and the formulation of smoke control strategies for highway tunnel projects such as the HK-Zhuhai-Macau immersed tunnel and the Shenzhen-Zhongshan immersed tunnel.

2.2.Full-scale experiments

Full-scale experiments can reflect real fire accident scenarios, and the reliability of the test results is high, making it the most effective research method for fire science. Full scale tests are usually conducted in abandoned or specially constructed and pre-operational tunnels, and in-depth analysis of test results can directly obtain empirical conclusions. These empirical or semi empirical formulas have good practicality. Meanwhile, experiments can simultaneously verify the accuracy of theoretical analysis and numerical simulation results.

In 1975, various ventilation system tests were conducted at the Zwenberg Tunnel in Australia, consisting of 29 groups. The tests mainly measured temperature, gas concentration, visibility, and combustion level in fire scenarios[1]. In 1980, the Public Works Research Institute (PWRI) in Japan mainly evaluated the effectiveness of rescue facilities, testing 8 groups in a 3300m highway tunnel[3]. In 1991, fire tests under a fire source power of 0.5-12MW was conducted in a small-scale tunnel with size of 130m×5.4m×2.4m, and a CFD fire simulation calculation program was proposed by Apte[4].The TST Tunnel Comprehensive Disaster Prevention Base in Spain mainly conducted tests on the ventilation system and fire extinguishing equipment. The test tunnel is a two-lane tunnel with a length of 600m. Every 150m, an emergency exit is set up through a detachable exhaust duct at the top for longitudinal, semi transverse, and mixed ventilation[5].

2.3.CFD numerical simulation

CFD numerical simulation technology specialized in reducing ground experimental workload, shortening development cycle, and saving experimental costs. By comparing with the model/full-scale experimental data, its correctness can be verified. The use of CFD technology can intuitively simulate the physical quantities such as velocity, temperature, and pressure of the airflow in the tunnel, and the results can serve as an important reference for optimizing ventilation modes.

Computational fluid dynamics (CFD) technology, which emerged in the mid-1980s, can simulate and predict the air flow pattern, temperature distribution and the development and distribution of high-temperature smoke in the environment. In recent years, it has been widely used in the ventilation of subway, railway and highway tunnels[6]. Many researchers in countries and regions have applied computational fluid dynamics technology to ventilation in tunnel fire accidents. Previous studies such as Brandies and Bergmann used a numerical combustion model to conduct two-dimensional numerical simulation research on various fire ventilation schemes for tunnel ventilation in 1983[7]. Subsequently, Cox and Kumar conducted a three-dimensional simulation of a vehicle fire in the King's cross tunnel in London in 1987. They conducted extensive research work in conjunction with the investigation of the fire, and studied the effects of radiation heat conduction and wall roughness on tunnel fires[8]. Fletcher conducting simulation studies on the effects of different ventilation speeds and fuel pool sizes since 1991. With the gradual improvement of computational models, computer simulation methods have been widely used to study the temperature field, smoke changes, and evacuation time and influencing factors of trapped personnel in tunnels after fire. Krol used FDS simulation to reproduce the process of fire development and demonstrated in detail the interactive effects of multi-factors on the number of threatened tunnel fires. They concluded that fire scale and traffic intensity have the greatest impact on the number of threatened tunnel fires. Seike proposed a quantitative evaluation method for fire safety in highway tunnels based on numerical simulation of smoke evacuation, and used CFD software to study the longitudinal distribution of smoke. Caliendo studied the change rule of temperature when different types of burning vehicles are in fire through CFD simulation, so as to determine the optimal distance of two-way highway tunnel emergency exit is about 350m.

3.Fire Field Characteristics

3.1.Heat Release rate

The power of the fire source, also known as the Heat Release Rate (HRR), is the most important parameter indicating the degree of fire development. Lemaire introduced the results of full-scale fire experiments in the Second Benelux tunnel and found that the maximum fire source power at a ventilation speed of 6m/s was consistent with that without ventilation. For well ventilated truck fires, the maximum fire source power is approximately 1.2 to 1.5 times that without ventilation[9]. Ingason conducted small-scale experiments under longitudinal (tunnel length direction) ventilation and point ventilation conditions, studying the influence of tunnel cross-section size and ventilation conditions on fire source power. The experimental results indicate that under ventilation conditions, the maximum fire source power in a tunnel is only 1.3 to 1.4 times that of an open space[10].

3.2.Ceiling temperature

In tunnel fires, the temperature below the ceiling is the key parameter for studying fire spread, structural protection, personnel evacuation, and emergency rescue. The factors affecting it are mainly the power of the fire source, fuel type, distance from the fire source to the ceiling, ventilation conditions, and distance to the fire source.

Alpert established a maximum temperature prediction model below the ceiling without sidewall restrictions. This model provides a simple and practical reference for calculating the maximum ceiling temperature in tunnel fires[11]. Based on the plume theory, Li theoretically analyzed the maximum ceiling temperature in tunnels, and found that it can be expressed in two regions, and verified the effectiveness of this theoretical model.

In terms of fire source characteristics, based on the theory of fire plume flow, Ji analyzed the constraint effect of sidewalls on the fire source, and conducted model experiments to establish a prediction model for the maximum ceiling temperature by changing distances from the end sidewalls and transverse sidewalls of a narrow space. On this basis, Zhou further conducted full-scale experiments and numerical simulations to study the variation pattern of the highest ceiling temperature in rectangular and arch section tunnels by changing distances from the fire source to the sidewall, and modeled for the highest ceiling temperature suitable for these two tunnel sections. Tang studied the influence of the aspect ratio of a rectangular fire source on the maximum ceiling temperature. A corresponding prediction model was constructed .

3.3.Smoke stratification characteristics

Simply put, the tunnel space during a tunnel fire can be divided into the upper hot smoke layer and the lower cold air layer. For tunnel and other building scenarios, the height of smoke layer interface can usually be determined according to the temperature, concentration of combustion products and visibility distribution.

Based on continuously changing smoke characteristic parameters, many methods have been proposed by previous researchers to calculate the position of the smoke layer interface. The most famous method is the N percentage rule proposed by Cooper of the National Institute of Standards and Technology in the United States. It is mainly based on the vertical temperature distribution (tunnel height direction) within the building structure, which is relatively convenient to use and has been confirmed by numerous studies related to building fire smoke.In order to avoid empiricism and subjectivity in the experimental data processing process, He proposed using the Least Squares method and the Integral Ratio method to determine the smoke layer interface. This method relates the overall distribution of physical quantities to the position of the smoke layer and does not depend on isolated measurement points. Ji studied the smoke movement characteristics of tunnel fires under different ambient pressure conditions through numerical simulation. The results showed that as the ambient pressure decreased, the temperature of the smoke increased and the mass flow rate of the smoke decreased.

3.4.Multiple fire sources

Due to vehicle collisions or fire spread, multiple sources of combustion often occur in tunnels. A collision between vehicles in a tunnel may cause two or more vehicles to burn simultaneously, while the spread of a fire may cause downstream targets to be ignited in sequence. In response to the scenario of multiple fire sources burning simultaneously, Chen conducted a double oil pool fire experiment in a narrow tunnel space, mainly studying the impact of different tunnel outlet sealing ratios on the combustion behavior of oil pool fires. Fan analyzed the mutual influence and combustion characteristics between the combustion rates of symmetrical double fire sources arranged horizontally in a longitudinal ventilation tunnel based on a scaled model tunnel experiment. Tsai investigated the effects of fire source spacing and power on the critical velocity of dual fire source scenarios in tunnels through small-scale experiments.

4.Ventilation Control For Highway Tunnel Fires

4.1.Ventilation principles for fire accidents

In the event of a fire in the highway tunnel, normal ventilation should immediately be changed to accident ventilation. The purpose of ventilation at this time includes: (1) Ventilation must be conducive to personnel escape and refuge, and try to avoid the phenomenon of high-temperature smoke backlayering in the tunnel under the longitudinal airflow, in order to create conditions for personnel refuge to the greatest extent possible. (2) Ventilation should reduce the temperature of high-temperature gases in the fire site to prevent damage to the tunnel enclosure structure caused by hot air flow. (3) Ventilation should be beneficial for firefighters to extinguish fires, allowing them to approach the fire from the windward direction and carry out firefighting work. (4) When personnel enter another parallel tunnel or level guide through a pedestrian crossing, accident ventilation should be able to prevent smoke from the burning tunnel from entering the pedestrian crossing and adjacent tunnels

4.2.Ventilation and smoke exhaust methods

When a fire occurs in a tunnel, the smoke from the fire poses a great danger and poses a serious threat to personnel inside the tunnel. During a fire, appropriate measures must be taken to control the spread of smoke to ensure the safe evacuation of trapped personnel in the tunnel and the firefighting and rescue work of firefighters. Natural smoke exhaust and mechanical smoke exhaust are the two main ventilation and smoke exhaust methods in tunnels.

4.2.1Natural ventilation

Natural ventilation refers to the use of mechanical equipment such as smoke exhaust fans, completely relying on the natural wind of the natural environment and the piston wind generated by the operation of cars in the tunnel to exhaust smoke outside the tunnel. Different natural wind directions and car driving directions may have different smoke removal effects. When the two are consistent, it helps to expel smoke. When the two directions are opposite, it is not conducive to the discharge of smoke. Vertical shaft natural smoke exhaust, as an emerging smoke exhaust method, is currently being adopted by more and more shallow buried tunnels in cities. This smoke exhaust method uses the chimney effect generated by the vertical shaft to exhaust smoke through the vertical shaft. Compared to traditional natural smoke exhaust methods, the pressure difference of the vertical shaft smoke exhaust is greater, which can achieve better smoke control effect.

4.2.2.Mechanical ventilation

Longitudinal, full horizontal, and semi horizontal ventilation are three typical mechanical ventilation and smoke exhaust methods. Longitudinal smoke exhaust refers to the use of axial flow fans or jet fans arranged at one end of a tunnel to form forced gas flow along the longitudinal direction of the tunnel. It is mainly suitable for unidirectional tunnels within 2500m and bidirectional tunnels within 1500m. This smoke exhaust method has a relatively low engineering cost and simple operation and maintenance, but the smoke exhaust effect is relatively poor. Full horizontal smoke exhaust refers to the formation of a flowing ventilation and smoke exhaust airflow at the cross-section of a tunnel through the collaborative action of a supply fan and a smoke exhaust fan. This smoke exhaust method can greatly reduce the spread and flow distance of fire smoke in the tunnel, and has the best smoke exhaust effect. However, its engineering cost and maintenance cost are also high, and it is often used in large and long highway tunnels. Semi horizontal smoke exhaust is a compromise ventilation and smoke exhaust method between longitudinal smoke exhaust and full horizontal smoke exhaust, which has good smoke exhaust effect and is mostly used in long tunnels around 3000m in lengt.

4.2.3.Critical Velocity

The longitudinal ventilation is the simplest and most widely used ventilation mode. The longitudinal ventilation and smoke exhaust mode has the advantages of small civil engineering quantity, low engineering cost, economic operating cost, and relatively simple control. There are also drawbacks such as long smoke exhaust paths during fires, long high-temperature zones in tunnels, and high post disaster repair costs. In the event of a fire in the tunnel, smoke will spread to both sides of the ignition point. The purpose of longitudinal ventilation is to prevent smoke backlayering, which means that the smoke flows downstream of the ignition point through longitudinal ventilation, ensuring that vehicles and personnel upstream of the ignition point are not affected by toxic smoke and high temperatures. Vehicles downstream of the ignition point continue to drive forward and exit the tunnel. This leads to the concept of critical velocity, which is the minimum longitudinal ventilation rate to prevent smoke backlayering.

There are many factors that affect the critical velocity of tunnel fires, including fire source heat release rate, blockage ratio, slope, tunnel cross-section shape, curvature, etc.According to the Guidelines for design of ventilation of highway tunnels (JTGT D702-02-2014), the critical velocities are specified as 2-3m/s, 3-4 m/s, and 4-5m/s based on different heat release rates (20MW, 30MW, 50MW). Roh studied the relationship between critical velocity and fire source heat release rate, and compared it with the smoke field and countercurrent length of on-site experiments. Li verified and studied the effect of fire source release rate on critical velocity. When the heat release rate of the fire source is small, the critical velocity of longitudinal ventilation in the tunnel is directly proportional to its power of 1/3[12].

Gannouni conducted numerical simulation research on the critical velocity of tunnel fires with and without obstacles, and found that the larger the vertical height between obstacles and the ground, the smaller the critical velocity. Lee and Tsai studied the impact of vehicle congestion on critical velocity through numerical simulation and model experiments. Huang believed that when the blocking ratio is small, the critical velocity is inversely proportional to the blocking ratio. When the blocking ratio exceeds 40%, there is no significant change in the critical velocity[13].

Chen used FDS software to simulate the critical velocity of tunnels with different slopes, with tunnel slopes of 10%, 5%, and 0%, respectively[14]. The conclusion drawn is that in downhill tunnels, the increase in slope has an increasing effect on the critical velocity, and the larger the slope, the greater it becomes. In uphill tunnels, an increase in slope has a reducing effect on the critical velocity, and the larger the slope, the smaller its value.Yi conducted 14 sets of fire experiments by changing factors such as fire heat release rate and tunnel slope. The conclusion is that as the slope increases from -3% to 3%, the critical velocity also gradually increases.

Emergency parking lots are usually set up in highway tunnels, and the tunnel section located in this area can be referred to as a sudden change in tunnel section compared to the conventional section. Sudden changes in cross-section can also have an impact on the critical velocity of a fire. Li used FDS software to conduct numerical simulation research on this issue, with a heat release rate of 30MW[15]. Through comparative research on the operating conditions of setting the section shape as widening and raising, with only widening and not raising, the conclusion is that the widening and raising situation has a higher space for smoke storage, and the escape environment is more ideal. In both cases of widening and raising, and only widening without raising, to completely prevent smoke backlayering, a higher ventilation speed is required.

He carried out a numerical simulation study on the influence of tunnel curvature on the transverse and longitudinal movement speed of fire smoke flow, and gave a critical wind speed of 4m/s when the heat release rate was 20MW[16]. It was concluded that smoke was affected by curvature, and the wall reflection made the smoke concentration distribution in the downstream section of the fire more uniform, which made it difficult to choose an escape route. Wang further conducted numerical simulations and concluded that the critical wind speed at a heat release rate of 10MW is 2.5m/s, and the smoke near the fire source downstream of the fire is asymmetrically distributed, with less smoke inside[17].

5.Conclusions

This article has reviewed research literature on highway tunnel fires. Firstly, based on the research methods, it summarizes the general methods for studying highway tunnel fires, including small-scale model experiments, full scale on-site experiments and numerical simulations, introducing the advantages and disadvantages of each method as well as application cases. Secondly, the research results on fire characteristic parameters of highway tunnels were presented, including heat release rate, ceiling temperature, and smoke stratification characteristics. Finally, in terms of tunnel ventilation, the main methods of tunnel ventilation were displayed, including natural ventilation and mechanical ventilation. At the same time, the most widely used longitudinal ventilation mode was shown, and the research progress on critical velocity was detailed. The influence of factors such as fire source heat release rate, blockage ratio, slope and curvature on critical velocity was summarized. The review work could provide theoretical and technical support for the fire safety and smoke control design of highway tunnels.

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