Research Progress on Smoke Control Technology for Highway Tunnel Fire

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Abstract. Fire is one of the biggest threats to the safe operation of highway tunnels, which will not only damage the tunnel structure, but also seriously threaten the people's lives and property. As a key link of tunnel fire rescue, ventilation and smoke control directly affects the development trend and hazard consequences of fire. Based on the previous research results, this paper introduces the characteristics of highway tunnel fire, the methods and characteristics of ventilation and smoke exhaust, the influence of tunnel structure, and fire extinguishing methods, which has certain reference and guiding significance for the design of fire ventilation and smoke exhaust, the personnel evacuation and emergency rescue in the highway tunnel.

1. Introduction
With the increasing investment in highway construction, China’s highway mileage is growing rapidly, and the number of highway tunnels is increasing year by year. In recent years, a series of major tunnel projects, such as Qinling Zhongnanshan Tunnel, Hong Kong-Zhuhai-Macao Immersed Tunnel and Humaling Tunnel, have completed successfully, indicating that China's tunnel technology is gradually moving towards a higher level. According to statistics[1], by the end of 2018, China had built 16,229 highway tunnels with a total length of 17,236,100 meters, including 1,058 extra-long highway tunnels (with a length of more than 3km) with a total length of 4,706,600 meters, and 4,315 long tunnels with a total length of 7,421,800 meters.

Table 1. Main relevant researches on tunnel fire in recent years.

| Research                        | Tunnel section size | Ventilation mode | Fire scenario | Research contents               |
|---------------------------------|---------------------|------------------|---------------|--------------------------------|
| Gwon Hyun Ko et al. (2010) [2]  | 0.4m(W)×0.4m(H)×10m(L) | Longitudinal ventilation | Pool fire | Influence of slope on critical velocity |
| Reference          | Dimensions          | Ventilation Method | Fire Type     | Description                                                                 |
|--------------------|---------------------|--------------------|---------------|-----------------------------------------------------------------------------|
| Ji et al. (2012)   | 2m(W)×0.88m(H)×6m(L)| Natural            | Pool fire     | Natural ventilation source fire position on ceiling temperature              |
| Lee et al. (2012)  | 0.6m(W)×7m(L) with 0.4-0.6m(H) | Longitudinal        | Vehicle fire  | Influence of vehicle blockage on critical velocity                          |
| Li et al. (2012)   | 0.25m(W)×0.25m(H)×12m(L) | Longitudinal        | Pool fire     | Influence of blockage ratio on critical velocity                            |
| Ahmed Kashef et al. (2013) | 0.7m(W)×0.32m(H)×15m(L) | Natural            | Pool fire     | Ceiling temperature distribution and smoke diffusion                        |
| Yi et al. (2014)   | 1.1m(W)×0.7m(H)×52.5m(L) | Longitudinal        | Pool fire     | Critical velocity in sloped tunnel fire                                     |
| Soufien Gannouni et al. (2015) | 0.25m(W)×0.25m(H)×12m(L) | Longitudinal        | Pool fire     | Influence of vehicle blockage on critical velocity                          |
| Zhong et al. (2015) | 1m(W)×0.5m(H)×8m(L)  | Longitudinal        | Pool fire     | Influence of transverse fire source position on critical velocity           |
| Tang et al. (2016) | 1.5m(W)×1.3m(H)×72m(L) | Longitudinal and ceiling central exhaust | Pool fire     | The relationship between back-layering length and ceiling central exhaust   |
| Wang et al. (2016) | Tunnel: 12.35m(W)×5.75m(H)×1410m(L) \ Shaft: 2.6m(W)×4.65m(H)×3.2m(L) | Natural            | Pool fire     | Influence of tunnel structure on smoke diffusion                           |
| Author(s)          | Tunnel Dimensions | Ventilation Method       | Fire Type    | Research Focus                                                                 |
|-------------------|-------------------|--------------------------|--------------|--------------------------------------------------------------------------------|
| Weng et al. (2016) [12] | 4.8m~20m(W) 4.2m~12m(H) | Longitudinal ventilation | Pool fire    | Influence of tunnel section coefficient and slope on critical velocity          |
| Ji et al. (2016) [13]       | 2m(L)×0.5m(H) with 0.4~1.0m(W) | Natural ventilation | Pool fire    | Influence of tunnel aspect ratio on ceiling temperature distribution           |
| Liu et al. (2017) [14]       | 5.2m(W)×3.4 m(H) | Natural ventilation | Pool fire    | Ceiling temperature distribution                                                |
| Liu et al. (2019) [15]       | 5.2m(W)×3.4 m(H) | Natural ventilation | Pool fire    | Influence of tunnel structure on smoke diffusion in contact area               |
| Liang et al. (2008) [16]     | NA                | Semi-transverse ventilation Volumetric heat source |               | The influence of different distance and number of vents on velocity field and temperature field |
| Men et al. (2018) [17]       | 100m(L)×5m(H) with 5~14m(W) | Natural ventilation | Pool fire    | Influence of slope and aspect ratio on smoke temperature                       |
| Liu et al. (2018) [18]       | NA                | Longitudinal ventilation Incense |               | Influence of longitudinal ventilation on smoke stratification                 |

Although the construction of a large number of highway tunnels has brought convenience to road traffic, it has also made the potential of vehicle accidents and fire in the tunnel gradually increase, which has brought great pressure to the safety of the tunnel during operation. Because the environment of the highway tunnel is relatively closed and the internal space is narrow, therefore, once the tunnel fire, the smoke will be difficult to timely discharge, in many cases will also cause secondary damage. The fire can also destroy internal structure of the tunnel, and seriously affect the escape of personnel and emergency rescue. As one of the key links of tunnel fire rescue, ventilation and smoke control have a directly impact on the development trend and hazard consequences of the fire. To address this
issue, extensive studies have been conducted via experiments and numerical simulations. Table 1 shows the main relevant researches on tunnel fire in recent years. A large number of research conclusions show that reasonable ventilation and smoke control can remarkably reduce the harm of the fire.

2. Characteristics of highway tunnel fire
Highway tunnel fire is mainly affected by its building structure, internal environment, fire location, and combustion materials. It mainly has the following characteristics:

(1) Traffic accidents are frequent. Compared with other highway sections, tunnels have more accidents, which are mainly affected by the greater difference in driving environment inside and outside the tunnel, as well as the visual and psychological changes of drivers. And traffic accident is one of the main causes of tunnel fire.

(2) Accident uncertainty. The uncertainty mainly includes the time, location, scale, cause of the fire, and composition of combustion materials. Due to the uncertainty, it is difficult to predict the occurrence and development of tunnel fire. In addition, the time of fire occurrence is also random, the peak hours of traffic, seasonality and other factors will all affect the rescue of fire.

(3) The fire hazard is great. Due to the narrow internal space of the tunnel, most of the tunnel fires are incomplete combustion, resulting in a large amount of smoke, and a large amount of toxic or harmful gases such as carbon monoxide. The smoke will seriously threaten people's lives and reduce the visibility, affecting the evacuation of personnel and emergency rescue.

(4) The fire spread fast and the rescue is difficult. The highway tunnel is long, narrow and closed, and it has few smoke vents. Therefore, the heat generated by the fire is not easy to be discharged timely, and the high-temperature smoke will be gathered, which makes the great temperature difference in the fire area. The high-temperature smoke is also affected by the piston effect and ventilation system, which makes the high-temperature smoke flow faster along the longitudinal direction in the tunnel. However, due to the small cross-section, narrow space, a large amount of high temperature smoke, and low visibility, it is easy to cause congestion in the tunnel, and the fire-fighting or rescue vehicles cannot reach the scene in time, which will easily cause panic and stampede accidents of the trapped personnel, and greatly increase the difficulty of rescue.

3. Typical ventilation methods in highway tunnel fire
Due to the hazards of fire smoke in the highway tunnels, it is necessary to control the smoke in the early stage of the fire, so as to gain more time for the personnel evacuation, emergency rescue, fire-fighting, and reduce the loss of personnel and property as far as possible[19]. At present, the ventilation and smoke exhaust of highway tunnels share a same system. Normally, the system is a ventilation system, while when a fire occurs, the system is converted into a smoke exhaust mode. Typical ventilation and smoke exhaust methods mainly include natural ventilation and mechanical ventilation, and the mechanical ventilation includes longitudinal ventilation, full-transverse ventilation and semi-transverse ventilation[20].

3.1. Natural ventilation
Natural ventilation is a kind of ventilation mode which exhausts the toxic and harmful gases in the tunnel without using any fan equipment, and it completely relies on the piston effect produced by natural wind and vehicle driving. There are three main reasons for the formation of natural wind flow in the tunnel: the temperature difference between the inside and outside of the tunnel (thermal potential difference), the horizontal pressure difference between the two ends of the tunnel (atmospheric pressure gradient) and the natural wind outside the tunnel[21].

When the temperature inside and outside the tunnel is different, the air density inside and outside the tunnel will be different, resulting in the air flow. This difference in pressure is called thermal potential difference, and the thermal potential difference is affected by the difference in air density inside and outside the tunnel and the difference in height inside and outside the tunnel. The cause of
horizontal pressure difference is that the difference of air temperature and humidity on the same horizontal level in a wide range of atmospheres. The difference in the air pressure is expressed by the atmospheric pressure gradient in meteorology, and the value can be inquired through relevant meteorological data. The natural wind outside the tunnel is the atmospheric wind blowing from the outside of the tunnel to the tunnel portal. And the pressure difference can be calculated from the wind direction and wind velocity of the natural wind outside the tunnel. The sum of thermal potential difference, horizontal pressure difference and natural wind pressure outside the tunnel is the power of forming natural ventilation in the tunnel[22]. When the natural wind direction in the tunnel is the same as the driving direction of the vehicle, the natural wind plays a role of assisting, and the time for exhausting toxic and harmful gases becomes shorter; while when the natural wind direction is opposite to the driving direction of the vehicle, the natural wind plays a role of resistance, and the time for exhausting toxic and harmful gases becomes longer.

3.2. Longitudinal ventilation
When the natural ventilation cannot meet the requirements of ventilation and smoke exhaust in the tunnel, the fans are needed, and this method of ventilation is called mechanical ventilation. Longitudinal ventilation is the most simple and effective method of mechanical ventilation. It is to install fans in suitable positions of the tunnel, and make the airflow in the tunnel flow along the tunnel longitudinally with the wind pressure produced by the fans, import fresh air from one end of the tunnel, and discharge smoke and harmful gases from the other end, so as to achieve the purpose of ventilation[23-25]. In the process of ventilation, dust and harmful gas in the tunnel will flow through the whole tunnel along the longitudinal direction. According to the adopted ventilation equipment, it can be divided into portal air-duct ventilation and jet fan ventilation. The portal air-duct ventilation mostly adopts axial-flow fans, while jet fan ventilation mostly suspends jet fans at the tunnel ceiling dispersedly, and a few installed at the tunnel portal. When the tunnel is long and the longitudinal ventilation cannot meet the requirements of the code, the tunnel can be divided into several ventilation sections by means of auxiliary channels such as vertical shaft, inclined shaft and parallel pilot tunnel, and this method of ventilation is called sectional longitudinal ventilation. According to the airflow supply form of the fans, the longitudinal ventilation can be divided into four types: blow-in type, suction type, dual-purpose type and combined type. Longitudinal ventilation has the characteristics of small construction difficulty, low construction cost and operation cost, and good utilization effect of piston wind. However, if the wind velocity of longitudinal ventilation is less than the critical velocity, the smoke on the ceiling of the tunnel will reflux. Longitudinal ventilation is suitable for one-way traffic tunnel within 3,000m and two-way traffic tunnel within 1,500m.

3.3. Full-transverse ventilation
In response to the carbon monoxide poisoning incidents caused by tunnel fires, the Holland Tunnel (circular shield) in New York City, USA, adopted a new method for exhausting harmful gases. It uses the lower bow space of the driveway arch space as air supply duct, and the upper bow space equipped with ceiling board as exhaust duct. This ventilation method of flowing the airflow from the lower space to the upper space through the tunnel is called full-transverse ventilation. Full-transverse ventilation has fans and air ducts for air supply and exhaust at the same time, forming the ventilation airflow flowing along the cross section of the tunnel, and the smoke can be discharged within a short distance along the longitudinal flow of the tunnel. This ventilation mode can effectively shorten the longitudinal flow distance of the smoke and reduce the hazard area, and minimize the disturbance of the smoke stratification, thus it is of great significance for the personnel evacuation and emergency rescue especially in the pre-fire period. In addition, the reliability of this ventilation mode is high, which makes it possible to build a long highway tunnel with large traffic volume, and it is widely used in the ventilation design of long highway tunnels.
3.4. Semi-transverse ventilation

The full-transverse ventilation mode requires two additional air supply and exhaust ducts, which will greatly increase the investment cost for tunnels with non-circular sections. Therefore, a compromise ventilation mode combining an air duct and a tunnel portal is adopted, which is the semi-transverse ventilation mode[26, 27]. This ventilation mode can be divided into two types: air supply semi-transverse and exhaust semi-transverse. When the tunnel is long, if the air supply semi-transverse ventilation is adopted, several shafts need to be set in the tunnel, and air supply duct also need to be set up, so that the fresh airflow will be sent into some parts of the tunnel, the smoke will flow along the tunnel longitudinally and be discharged from the tunnel portal finally.

Among these ventilation modes, the main purpose of ventilation is to provide fresh airflow and exhaust smoke, so as to ensure personnel evacuation, temporary refuge and emergency rescue in case of tunnel fire. Therefore, there should be no high-temperature smoke around the air supply duct, otherwise, the toxic and harmful smoke discharged will be sent back to the tunnel, which will aggravate the severity of the accident. Thus, the design of fresh air supply duct position should be reasonable, and measures to prevent smoke reflux are required if necessary.

4. Influence of tunnel structure on fire smoke control

4.1. Tunnel slope

During the development of highway tunnel engineering, some lines may be affected by geological conditions and other factors, and a sloped line with the characteristics of long and continuous downhill can be designed and constructed. In the design of ventilation of highway tunnel, especially the extra-long highway tunnel, if the influence of tunnel slope and stack effect are not considered, the actual smoke control effect may be different from the design effect in the case of tunnel fire, even the extremely dangerous consequences will be caused. Compared with ordinary tunnels, the effect of fire wind pressure is remarkable when fire occurs in a sloped tunnel, and the stack effect increases the difficulty of tunnel fire smoke control.

Stack effect is a special phenomenon in the case of sloped tunnel fire, which makes the smoke spread strongly in the direction of the tunnel uphill[28, 29]. Especially in the extra-long highway tunnel, the tunnel length is long and the height difference between the two ends of the tunnel is large, so that the smoke will spread towards the uphill direction rapidly which driven by buoyancy, thermal potential difference and atmospheric pressure gradient. The buoyancy of stack effect is shown as Eq. (1)[30].

\[
\Delta P_{\text{stack}} = J_f L_f \rho_0 g \eta_f \frac{\Delta T_f}{T_f}
\]  

Where \( \Delta P_{\text{stack}} \) is the buoyancy of stack effect, \( J_f \) is the tunnel slope, \( L_f \) is the length of fire area, \( \rho_0 \) is the air density of fire area, \( g \) is the gravity, \( \eta_f \) is the blockage ratio, and \( \frac{\Delta T_f}{T_f} \) is the dimensionless temperature.

The stack effect has both advantages and disadvantages to the ventilation in the tunnel fire[31]. When the driving direction in the tunnel is uphill, the stack effect can make the smoke gather in uphill direction, reduce the influence on the vehicles and people trapped in downhill direction, and is beneficial to the ventilation; while when the driving direction in the tunnel is downhill, because of the stack effect, the smoke gathers in the uphill direction of tunnel, the vehicles blocked by fire are also in the uphill direction, so the smoke is really dangerous to the trapped vehicles and people, and stack effect is not conducive to ventilation, even increases the difficulty of smoke control in the extra-long highway tunnel fire.

4.2. Tunnel curvature radius

The smoke diffusion of curved tunnel is different from that of the straight tunnel. At present, there are relatively few studies on the curved tunnel fire, especially on the influence of curvature and ventilation
mode for the curved tunnel fire[32]. Curvature radius is an important parameter of curved tunnel, which represents the degree of curvature of the arc line.

Generally, in terms of the main tunnel facilities, some facilities in the curved tunnel have some similarities with the long straight tunnel in terms of setting. Therefore, in the design of fire-fighting facilities and ventilation system, it can refer to the relevant highway tunnel design code. However, compared with the long straight tunnel, the smoke control in the curved tunnel is more difficult. In most cases, if the longitudinal airflow velocity is higher than the critical velocity in the long straight tunnel when fire, people in the upstream area will not be affected by the back-flow of smoke, while in the curved tunnel, it is not enough. In addition, once the velocity of longitudinal ventilation is unreasonable, it is easier to allow a large number of high-temperature smoke gathered in the curved section and spread rapidly throughout the tunnel, thus seriously threaten the evacuation of trapped people and vehicles.

The large curvature of curved tunnel will slow down the attenuation of temperature and increase the mixing of smoke. The curvature radius of the tunnel will affect the attenuation distance of the smoke, and the larger the curvature radius is, the longer the attenuation distance is, the closer it is to the long straight tunnel. Due to the influence of eddy motion and convection in the curved tunnel, a large amount of cold air is sucked into the hot smoke, which is different from the long straight tunnel, the influence of curvature makes the temperature above the fire source higher than other sections, and the fire plume is inclined because of ventilation. The force of fluid flowing through curved surface at different curvature of curved tunnel will accelerate the mixing of smoke in the tunnel, and the smoke will continuously impact the walls at both sides of the curved section area during the movement, which makes the flow velocity significantly increase; because of the curvature, the interface area at the curved section is generally larger than that of the general straight section, and the curvature of the tunnel has a negative correlation with its local section area. In addition, for the same fire substance, the heating expansion area of air near the fire source is the same, so the larger the curvature, the larger the area, the greater the friction resistance of the smoke to the wall of tunnel ceiling. The smoke spreading state is different in the curved tunnel[33]. In the stage of fire development, the oxygen is enough, the fire developing fast, and the smoke temperature rises rapidly; in the stage of fire steady, the temperature of smoke reaches the highest value and be stable, due to the convection of sucked cold air with hot smoke, and cooling effect of tunnel wall to the hot smoke, the temperature of the smoke decreases gradually with the increase of the distance from the fire source, the temperature gradient of smoke is relatively smaller at a farther position from the fire source, and the temperature will reduce to the ambient temperature finally, it indicates that the influence area of hot smoke in the curved tunnel fire is limited.

4.3. Tunnel blockage ratio

When a fire occurs in a highway tunnel, the blockage ratio and the shape of the tunnel section will have a great influence on the diffusion characteristics of smoke. Tunnel blockage ratio is the ratio of the cross-section of the blockage to the full cross-section of the tunnel. The blockage ratio is shown as Eq. (2)[34].

$$\beta = \frac{A_{\text{total}} - A_{\text{block}}}{A_{\text{total}}} \times 100\%$$

Where $\beta$ is the tunnel blockage ratio, $A_{\text{total}}$ is the full cross-section of the tunnel, and $A_{\text{block}}$ is the cross-section of the blockage.

Previous researches[35-37] show, with the increase of blockage ratio, the smoke velocity in the circular section tunnel increases, and increases at first then decreases in the rectangular section tunnel under the same fire power and no ventilation condition, in addition, when the blockage ratio is the same, the smoke velocity in the circular section tunnel is higher than that in the rectangular section. When both at the critical velocity, the influence of blockage ratio on the ceiling temperature is mainly concentrated on the upper part of the fire area, with the increase of blockage ratio, the maximum
ceiling temperature increases, and when the blockage ratio is the same, the maximum ceiling temperature of circular section tunnel is higher than that of rectangular section tunnel.

5. Influence of fire extinguishing methods on smoke control

5.1. Water mist fire suppression
As a substitute environmentally friendly fire extinguishing method, water mist fire suppression has developed rapidly in recent years. The linkage control with other systems can enable the water mist fire suppression to suppress fire effectively. The water mist fire suppression system consists of water source, water supply equipment, pipe network, filter device, nozzle and fire control linkage system[38]. In general, the higher pressure of the water, the better performance of the water mist diffusion, while the requirements for all parts of the system is also higher. The formation of water mist consists of two processes[39-41], the first step is to form water jet or thin water film through the water mist nozzle due to the pipeline pressure; and the second step is to form water droplets with small particle size due to the strong collision between the atmosphere and water jet or thin water film. The mechanism of water mist fire suppression is mainly the physical properties, including vaporization and heat absorption (droplets in the process of vaporization absorb heat from the fire area, the more heat absorbs, the more conducive to reduce the temperature, in which the droplet size is directly proportional to the vaporization and heat absorption capacity), surface cooling (compared with the advantages of small droplet size in vaporization and heat absorption, surface cooling requires that the droplets penetrate the flame area to reach the fuel surface with enough momentum, thus larger droplet size and higher initial velocity have advantages), oxygen isolation and asphyxiation (after the water mist enters the fire area, due to the vaporization, its volume expands to about 1,600 times of the original volume under the standard atmospheric pressure, as the temperature of the fire area decreases, vaporization is limited, and the effect will be reduced), and reduced thermal radiation (both droplets and water vapor can reduce the thermal radiation).

The influence of water mist opening on the downstream temperature is greater than that on the upstream temperature. Different spray angles of water mist have a great impact on the fire suppression effect in the highway tunnels, adopting appropriate spray angles of water mist can increase the overlap area between the adjacent water mist nozzles and enhance the superposition effect of water mist. Ceiling ventilation is also very effective for smoke control and can reduce the temperature of the tunnel, but it is not that the earlier the ventilation is, the better to the water mist suppression. When the fire power is 4MW, the water mist and the ventilation system start at the same time can make the effect reach to the best. Water mist can cool fuel surface temperature, which is the key to the fire extinguishing, and the airflow velocity will have a greater impact on the vertical velocity of water mist droplets, thus affect the fire extinguishing effect. The mode of longitudinal ventilation with downstream smoke exhaust can effectively make up for the disadvantages of both the tunnel ceiling smoke exhaust and longitudinal ventilation, because it can prevent smoke reflux. The mode of fresh air supply on both sides with smoke exhaust in the middle section can effectively gather the smoke in the middle of the tunnel, and smoke exhaust which set at the middle tunnel can prevent the smoke reflux and inhibit the smoke spread in the downstream of the tunnel, which is beneficial to evacuation[42].

5.2. Plugging fire suppression
When the conventional rescue method cannot achieve effect, in order to ensure that the highway tunnel fire can be timely put out, the plugging fire suppression was carried out, and it has a positive impact on the highway tunnel fire rescue. In highway tunnel fire, due to the narrow space, the environment of fire area is relatively harsh, so that the firefighters need to bear a great risk both physical and psychological, moreover, if there is a collapse accident at fire area, it will cause a serious threat to the safety of firefighters. Therefore, it is necessary to fully understand the situation of the fire and take effective fire-fighting measures, and the plugging fire suppression technology can solve this
problem well. The biggest advantage of plugging fire suppression is that the oxygen quantity in the highway tunnel can be reduced rapidly through the effective closure of the entrance and exit of the highway tunnel, and the fire can be extinguished due to insufficient oxygen in the combustion process by means of suffocation[43]. This type of fire extinguishing measures only need to seal the entrance and exit of the tunnel and other vents, do not require large fire-fighting equipment or firefighters. In addition, the difficulty of this technology is relatively low, and the implementation speed is relatively fast. Therefore, the plugging fire suppression technology has great advantages in the process of tunnel fire-fighting, and it has achieved positive results in the actual application.

6. Conclusion
In this paper, the characteristics of highway tunnel fire, typical ventilation modes, the influence of tunnel structure and fire extinguishing methods on the smoke diffusion are introduced in detail, which are important for the design of tunnel fire control, smoke exhaust, personnel evacuation and emergency rescue of highway tunnel.

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