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Study on the reasonable smoke exhaust rate of the crossrange exhaust duct in double-layer shield tunnel

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Abstract

The research on the concentrated smoke extraction system of crossrange exhaust duct in double-layer shield tunnel is still very lack in the world. This paper is on the smoke extraction system of double-layer shield tunnel. It will provide the supports and references for the smoke control of tunnel fire and the determination of related technical parameters in the design of tunnel fire ventilation and smoke extraction, so it has important scientific value, practical significance and application prospects. This paper bases on the tunnel project of Slender West Lake in Yangzhou. By using the method of combining theory and numerical simulation, a conclusion can be drawn that the reasonable smoke exhaust rate of the upper tunnel is 140 m^3/s.

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Keywords: double-layer tunnel; shield tunnel; the crossrange smoke duct; smoke exhaust rate

Nomenclature

c_p	constant pressure specific heat, kJ/kg/K
M_p	mass flow of the plume, kg/s
Q	heat release rate from fire, kW
Q_c	convection heat release rate from fire, kW
T	average temperature of the smoke, K
T_0	temperature of ambient, K

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V	smoke-generation rate from fire, m^3/s
z	height from the surface of fuel to the bottom of the smoke layer, m
z_l	limit height of the flame, m
ρ_0	density of ambient, kg/ m^3

1. Introduction

With the rapid development of economy in China, it owns the largest tunnels and the fastest growing on tunnels in the world. The problem of tunnel safety is more and more serious because of the increase of the tunnels' length and the vehicles' running speed.

The damages of the tunnel fire are mainly caused by the diffusion of heat and smoke from the fire. These heat and smoke always endanger the people's safety in the tunnel, damage the vehicles and their supplies as well as the tunnel itself facilities (including ventilation and lighting equipment, monitoring equipment, communication equipment, wire and cable, etc.). In addition, once the fire occurs in the tunnel, it will inevitably affect the operation of the entire traffic line, and even lead to traffic jams and disrupted. These effects may last for few weeks, months or even longer time [1]. Therefore, in order to reduce all kinds of damages and losses above and ensure the safe evacuation of persons and vehicles in a fire, it is necessary to study how to control the tunnel fire effectively; thus studying the smoke extraction system of tunnel is required.

In the concentrated smoke extraction mode, there are usually three kinds of independent exhaust ducts: (1) to set partitions at the top of the tunnel to form an independent exhaust duct; (2) to set an independent exhaust duct at the bottom of the roadway in the tunnel; (3) to set an independent auxiliary tunnel which is separate from the main tunnel as an exhaust duct. It has been studied comprehensively to set independent exhaust duct at the top of the tunnel in the world, while the research on the concentrated smoke extraction system of crossrange exhaust duct in double-layer shield tunnel is still very lack. Therefore, this paper that is on the smoke extraction system of double-layer shield tunnel will provide the supports and references for the smoke control of tunnel fire and the determination of related technical parameters in the design of tunnel fire ventilation and smoke extraction, so it has important scientific value, practical significance and application prospects.

2. Engineering Situation

This study bases on the tunnel project of Slender West Lake in Yangzhou. The tunnel is on the main road in the medium-sized city. The length of the upper tunnel is 1789m, and the length of the lower tunnel is 2350m. The design speed is 60 km/h in the major section of the tunnel, while the design speed is 60 km/h in the ramps. The tunnel will be four lanes. The lane width is 3.5m+3.5m in one direction (the width of ramps is 3.5m+2.5 m) and the height of the lane is 4.5 m.

The concentrated smoke extraction system is applied in the double-layer tunnel, the upper and lower smoke vents share a communal exhaust duct that located on the right side of the tunnel, as shown in Fig. 1. When a fire occurs in one layer of the tunnel, smoke vents near the fire will be opened and the fans at the two ends of the tunnel will operate, then the smoke enter the exhaust duct though the smoke vents and are drawn out by the fans in the exhaust duct. In order to prevent the fire from spreading to another layer of the tunnel, smoke vents of another layer are closed when the fire breaks out. Therefore, the upper and lower layers can be viewed as a separate tunnel, the research methods of each layer are similar to each other, but the distribution laws of technical parameters are different. Due to limitations on space, this paper only select the shield part of upper tunnel to study. The fire scale is determined as 20MW by studying, and the longitudinal ventilation velocity is 1 m/s by the design, under these conditions, the reasonable smoke exhaust rate of the upper layer of the double-layer shield tunnel will be determined by the methods of combining theory and numerical simulation.

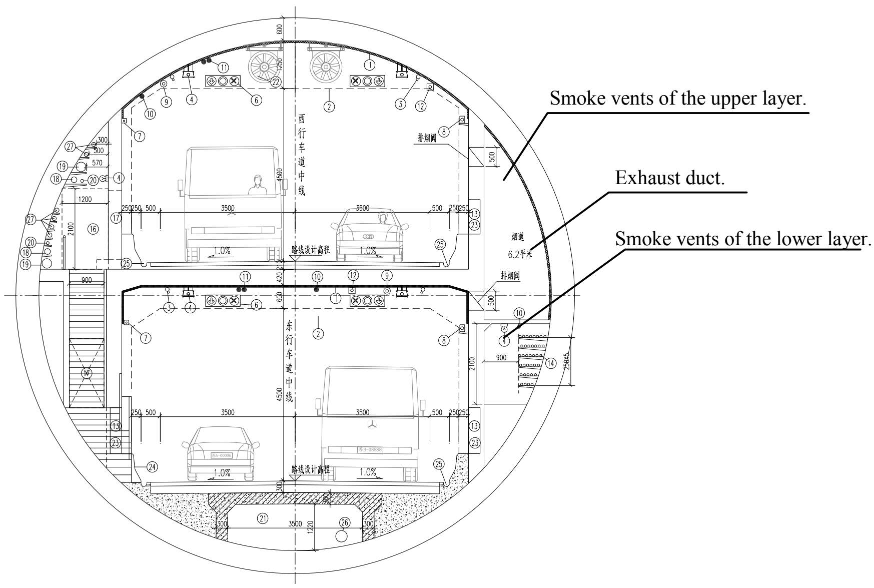

Fig. 1. A cross- sectional image of the double-layer shield tunnel.

3. Theoretical analysis and calculation of the smoke exhaust rate

The smoke extraction rate depends largely on the smoke-generation rate while the smoke-generation rate depends largely on the mass flow of the plume above the fire. Based on *Building Smoke Control Code*（DGJ08-88-2006）and the actual situation of the tunnel project of Slender West Lake in Yangzhou, the axisymmetric plume model can be taken to calculate the theoretical smoke exhaust rate.

$$M_p = \begin{cases} 0.032Q_c^{3/5}z & , \; z \le z_l \\ 0.071Q_c^{1/3}z^{5/3} + 0.0018Q_c & , \; z > z_l \end{cases} \tag{1}$$

In equation (1), $z_l = 0.166Q_c^{2/5}$, $Q_c \approx 0.7Q$.

The value of 'z' should not be less than the minimum clear height, and the minimum clear height is taken as 2 m. Assume that the surface of fuel is on the roadway, the bottom of smoke layer is the bottom of the tunnel rock when all the smoke is discharged. Therefore, 'z' should be the height of the upper tunnel. In the tunnel project of Slender West Lake, z=5.75 m.

When the fire scale of vehicles in the tunnel is 20 MW,

$$z_l = 0.166\,Q_c^{2/5} = 7.561>5.75$$

So z_l is more than z. Therefore,

$$M_p = 0.032\,Q_c^{3/5}z = 0.032 \times （0.7 \times 20000）^{3/5} \times 5.75 = 56.56\,kg/s$$

When mass flow of the plume, M_p, is known, the smoke-generation rate can be calculated according to equation (2).

$$V = \frac{M_p T}{T_0 \rho_0} \tag{2}$$

In equation (2), generally $\rho_0 = 1.2$ kg/ m³, $T_0 = 293$ K.
The value of 'T' can be calculated by the equation (3):

$$T = T_0 + \frac{Q_c}{M_p c_p} \tag{3}$$

In equation (3), $c_p = 1.02$ kJ/kg/K, $T_0 = 293$ K.

According to equation (3), absolute temperature of the smoke can be calculated:

$$T = T_0 + \frac{Q_c}{M_p c_p} = 293 + \frac{14000}{56.56 \times 1.02} = 535.68\, K$$

Importing the value of T, M_p, ρ_0 and T_0 into equation (2), the smoke-generation rate of the upper tunnel can be calculated:

$$V = \frac{M_p T}{T_0 \rho_0} = \frac{56.56 \times 535.68}{293 \times 1.2} = 86.17\, m^3/s$$

In conclusion, when the fire scale of the tunnel is 20 MW, the required minimum smoke exhaust rate of the upper tunnel shall be more than the smoke-generation rate (i.e. 86.17 m³/s) to ensure that all the smoke produced by fire is discharged.

4. Criterions to determine the reasonable smoke exhaust rate

The problems is that the smoke exhaust rate is not enough when we use the smoke-generation rate obtained by the classical plume model to design the smoke exhaust rate of the concentrated exhaust system in the tunnel. Therefore, it is necessary to optimize the smoke exhaust rate of the exhaust system from the perspective of the smoke control effects. The criterions of the smoke control effects as follows:

4.1. Criterions for the structural safety of the tunnel

National Institute of Standards and Technology (NIST) points out that, the strength of the high-strength concrete (HSC) will decline when the temperature reaches 380 ℃, while the compressive strength of the HSC will loss 40% at 450 ℃ and will loss 75% at 600 ℃. In addition, when the temperature is 600 ℃, the yield stress of steel will fall below a third of the yield stress at room temperature. Therefore, the tunnel fire may do a heavy damage to the structures of the tunnel and reduce the reliability of the structural system of the tunnel when the temperature exceed 600 ℃ [1].So the temperature of the tunnel rock should not exceed 600 ℃.

4.2. Criterions for the micro-environment of evacuation

As shown in *Fire Engineering Guidelines*, to ensure the evacuation from the tunnel fire, the temperature of 2 m above ground should be less than 60 ℃ and the visibility of 2 m above ground should exceed 10 m in the tunnel [2].

4.3. Other criterions

When the inner surface of the exhaust duct is built with sleek concrete or other nonmetal materials, the flow rate in the exhaust duct should not exceed 15 m/s, while the flow rate should not exceed 20 m/s when the inner surface is built with metal materials; the design flow rate in the exhaust duct should be between 13 m/s and 18 m/s[3]. So the flow rate in the exhaust duct should not exceed 18 m/s.

In addition, smoke vents of the tunnel should automatically shut down at 280 ℃; fans in the exhaust duct must be able to run continuously more than 1.0 hour at 250 ℃ [3]. So the highest temperature of smoke vents is 280 ℃, while the highest temperature of fans is 250 ℃.

5. Numerical simulation on reasonable smoke exhaust rate of the upper tunnel

The Fire Dynamics Simulation (FDS) is being developed at NIST to study fire behavior and to evaluate the performance of fire protection systems in buildings [4]. It is a Computational Fluid Dynamics (CFD) model of fire-driven fluid flow. The model solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The partial derivatives of the conservation equations of mass, momentum and energy are approximated as finite differences, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate smoke movement, sprinkler discharge, and fuel sprays [5].

Consider the smoke-generation rate of the upper tunnel is 85.76 m^3 / s, so the three kinds of the smoke exhaust rate (100 m^3 / s, 120 m^3 / s and 140 m^3 / s) are adopted to do numerical simulations. The coordinate of the fire resource is set to 0 m, there are two smoke vents at the upstream of fire and three smoke vents at the downstream of fire. The fire scale is 20 MW. The longitudinal ventilation velocity is 1 m/s and the wind blows from upstream to downstream (i.e. the wind blows from left to right of the tunnel). At each end in the exhaust duct of the tunnel there is a fan to discharge the smoke. Working conditions of the smoke exhaust rate as follows:

Table 1. Working conditions of the smoke exhaust rate.

No.	Heat release rate (MW)	Slope(%)	Longitudinal ventilation velocity(m/s)	The area of smoke vents (m^2)	The interval of smoke vents (m)	Smoke exhaust rate (m^3/s)
A1	20	0	1	6×0.5	60	100
A2	20	0	1	6×0.5	60	120
A3	20	0	1	6×0.5	60	140

As shown in Table 1, FDS is applied to carry out numerical simulations for the length of 800 m (-300 m~500 m) of the upper tunnel model. The results and related analysis is seen below.

5.1. Temperature distribution of 2 m above ground

The Fig. 2 shows that, when the smoke is steady, it is the same with the changing laws of temperature distribution of 2 m above ground under the working conditions of A1 to A3, i.e. all the areas of high temperature are close to the fire, and the temperature rapidly falls to the environment temperature (20℃) with the increase of the distance from the fire. The highest temperature of each the working condition exceeds the specified 60℃, but all the temperature that are in the temperature-affected areas are below 60℃. In addition, both the highest temperature of A2 (120 m^3 /s) and the highest temperature of A3 (140 /s) are higher than the highest temperature of A1 (100 m^3 /s), and in these three working conditions, only the temperature-affected areas of A3 are narrowest (-200 m~150 m) and the temperature control effect of A3 is better than other working conditions.

In conclusion, when the fire scale is 20 MW and the longitudinal ventilation velocity is 1 m/s, the smoke exhaust rate taken as 140 m^3 /s is the best for evacuation.

5.2. Temperature distribution of the tunnel rock

The Fig. 3 shows that, when the smoke is steady, it is the same with the changing laws of temperature distribution of the tunnel rock under the working conditions of A1 to A3, i.e. all the high temperature areas are close to the fire, and the temperature of the tunnel rock follows the diminishing exponential distribution with the increase of the distance from the fire. In these three working conditions, only the highest temperature of the tunnel rock of A3 (140 m3/s) is below the specified 600℃ and will not damage reinforced concrete structures, the highest temperature of the rest two working conditions are a little more than 600℃. In addition, only the temperature-affected areas of A3 are narrowest (-250m~175m), and they have the least impact on the structures of tunnel.

In conclusion, when the fire scale is 20 MW and the longitudinal ventilation velocity is 1 m/s, the smoke exhaust rate taken as 140 m3/s is the best for the structures of tunnel.

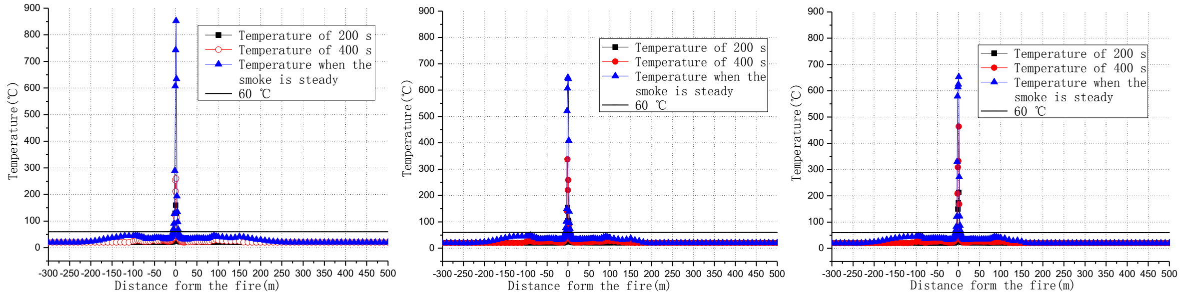

Fig. 2. (a) temperature distribution of 2 m above ground in A1 (100 m^3/s); (b) temperature distribution of 2 m above ground in A2 (120 m^3/s); (c) temperature distribution of 2 m above ground in A3 (140 m^3/s).

5.3. Visibility distribution of 2 m above ground

The Fig. 4 shows that the minimum visibilities in the visibility-affected areas of all the working conditions are below the specified 10 m when the smoke exhaust rate is 100 m^3/s or 120 m^3/s. When the smoke exhaust rate is 140 m^3/s, only the minimum visibility in the visibility-affected areas of downstream of fire is lower than 10m. In addition, it also can be seen that the visibility-affected areas in the tunnel are becoming narrower gradually and the visibilities show an upward tendency with the increase of the smoke exhaust rate at the same exhaust vents settings. Overall, the changing laws of the visibility are relatively consistent and the visibilities show little change under the working conditions of A1 to A3.

By comparing the working conditions of A1 to A3, it shows that, from the fire resource to the visibility-affected areas, smoke layer constantly sinks down and the visibilities decrease gradually with the temperature of the smoke dropping; while the visibilities gradually rise outside the scope. It indicates that smoke is basically controlled within a certain range of smoke vents (-93m−-87m, -33m−27m, 87m−93m and 147m−153m). Hence, when the fire scale is 20 MW and the longitudinal ventilation velocity is 1 m/s, the smoke exhaust rate taken as 140 m3/s is the most suitable for evacuation.

According to the above analysis, a preliminary conclusion may be drawn that the smoke exhaust rate taken as 140 m^3/s is the best. Next we just need to check the rest parameters such as the flow rate in the exhaust duct, the temperature of the smoke vents and the fans when the smoke exhaust rate is 140 m^3/s, then to determine whether the rest technical parameters conform to the corresponding criteria or not.

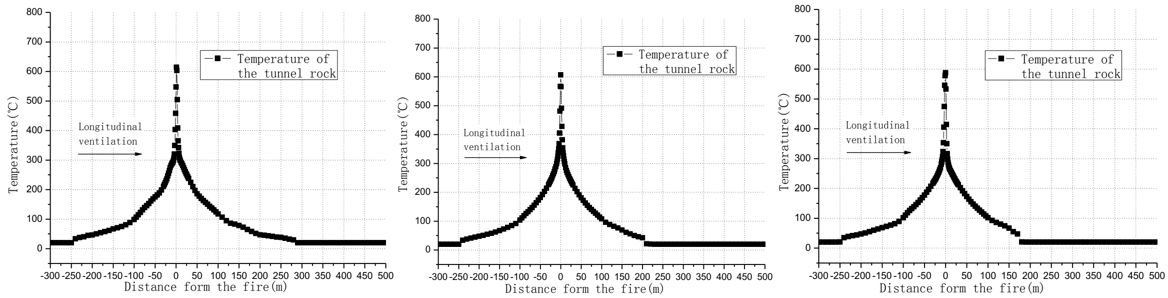

Fig. 3. (a) temperature distribution of the tunnel rock in A1 (100 m^3/s); (b) temperature distribution of the tunnel rock in A2 (120 m^3/s); (c) temperature distribution of the tunnel rock in A3 (140 m^3/s).

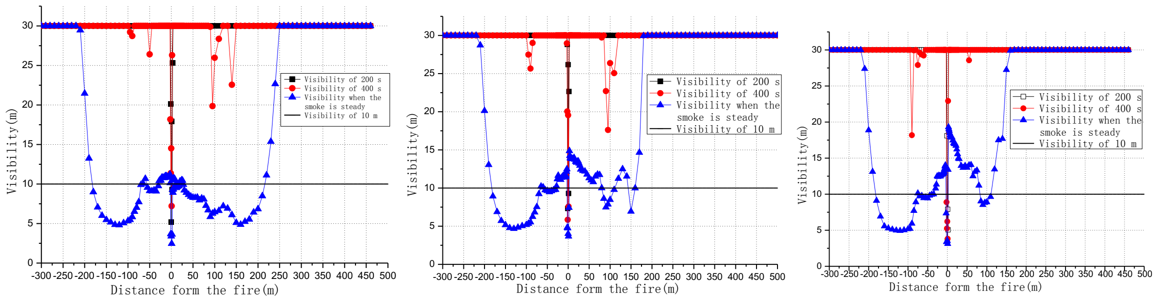

Fig. 4. (a) visibility distribution of 2 m above ground in A1 (100 m³ /s); (b) visibility distribution of 2 m above ground in A2 (120 m³ /s); (c) visibility distribution of 2 m above ground in A3 (140 m³ /s).

5.4. Checking of the rest technical parameters

Fig. 5 under the condition of the 20 MW fire shows that, the flow rates in the exhaust duct increase gradually with the increase of the distance from the fire when the smoke is steady, the curve of flow rates has a mutation at the corresponding periods of smoke vents. This is because there are a lot of smoke swarming into the exhaust duct and increasing the volume flow of smoke in the exhaust duct. As shown in Fig. 5, when the smoke exhaust rate is 140 m^3/s, all the flow rates in the exhaust duct are below the specified 18 m/s and conform to the corresponding criterion.

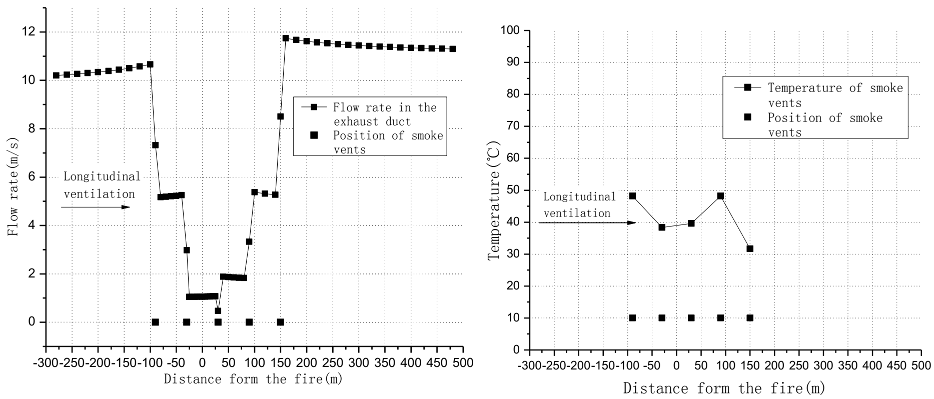

Fig. 5. (a) flow rate distribution in the exhaust duct in A3 (140 m³ /s); (b) temperature distribution of the smoke vents in A3 (140 m³ /s).

Table 2 shows that, when the fire scale of tunnel is 20 MW, the temperature of all the smoke vents are below 55 ℃ and are less than the specified 280 ℃, it will not damage the smoke vents; on the other hand, the temperature of fans are below 30 ℃ and are also less than the specified 250 ℃, and the fluctuations of the temperature curve of fans are not significant. It will keep the smoke vents and the fans to work normally. Therefore, when the fire scale is 20 MW and the longitudinal ventilation velocity is 1 m/s, the temperature of smoke vents and fans does not affect the selection of smoke exhaust rate. In addition, as shown in Fig. 5, the temperature of smoke vents is far less than the specified 280 ℃, also conform to the corresponding criterion.

In conclusion, when the smoke exhaust rate is taken as 140 m^3/s, the technical parameters basically meet the corresponding criteria and the smoke control effect is the best. Therefore, the reasonable smoke exhaust rate of the double-layer shield tunnel of Slender West Lake in Yangzhou should be 140 m^3/s.

Table 2. The temperature of smoke vents and fans.

No.	Heat release rate (MW)	Longitudinal ventilation velocity(m/s)	Smoke exhaust rate (m^3/s)	The area of smoke vents (m^2)	The interval of smoke vents (m)	The temperature of smoke vents (℃)					The temperature of the fan on the upstream (℃)	The temperature of the fan on the downstream (℃)
						U1	U2	D1	D2	D3		
A1	20	1	100	6×0.5	60	49.3	41.9	34.7	48.1	43.8	22.6	21.9
A2	20	1	120	6×0.5	60	50.0	38.2	38.0	48.5	40.0	23.1	21.7
A3	20	1	140	6×0.5	60	48.2	38.3	39.6	48.2	31.7	23.1	21.6

6. Conclusions

(1) The article applies the axisymmetric plume model to calculate the smoke-generation rate of the tunnel project of Slender West Lake in Yangzhou, and to draw a conclusion that the theoretical smoke-generation rate is 86.17 m^3/s.

(2) The required technical parameters for studying the reasonable smoke exhaust rate and their corresponding criterions are determined by various standards, criteria, and related information.

(3) FDS is applied to do numerical simulations for the shield part of the upper tunnel. Based on the visibility distribution of 2 m above ground and the temperature distribution of 2 m above ground and tunnel rock, a preliminary conclusion is drawn that the smoke exhaust rate can be taken as 140 m^3/s.

(4) Checking the rest parameters including the flow rate in the exhaust duct, the temperature of the smoke vents and the fans when the smoke exhaust rate is 140 m^3/s, then the rest technical parameters can be found that conform to the corresponding criteria. Therefore, the reasonable smoke exhaust rate of the double-layer shield tunnel of Slender West Lake in Yangzhou should be 140 m^3/s with the comprehensive consideration.

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