

Numerical Studies on the Smoke Control Parameters of Water Mist Screens with Transverse Ventilation System in Tunnel Fires



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Abstract Emergency ventilation systems are commonly used for smoke control during tunnel fires. Numerical results show that the fire and smoke would be confined effectively by the water mist screen and transverse ventilation system (WMSTV system) system, and the environment inside the confined zone would be suitable for occupants' evacuation and fire fighting. In this paper, the smoke control parameters of WMSTV system are proposed. The visibility distributions and smoke extraction efficiency are analyzed by FDS simulation. The results show that the minimum spacing distance between smoke vents should not be less than 40 m, while the maximum spacing distance should not exceed 60 m for 30 MW of fire. The spacing distance between the screen and vent is suggested to fall in 30–45 m. Two vents are recommended in the control zone with the screen spacing of 120 and 150 m. Four vents are recommended in the control zone with the screen spacing of 180 m.

Keywords Smoke control · Water mist screen transverse ventilation · Tunnel fire · Visibility · Smoke extraction

Nomenclature

- D^* Characteristic fire diameter (–)
 H Heat release rate from fire (kW)
 T_0 Temperature of ambient (K)
 σ Empirical constants (–)
 d_m Median droplet diameter (μm)
 η_i The smoke extraction efficiency of vent i
 Q_i The smoke extraction rate of the single vent i

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L_1	Distance of smoke vents (m)
ρ_0	Density of ambient (kg/m^3)
c_p	Constant pressure specific heat [$\text{kJ}/(\text{kg K})$]
g	Acceleration of gravity (m/s^2)
d	Droplet diameter (μm)
η	Smoke extraction efficiency
Q	The total smoke generation rate (kg/s)
L	Distance of water mist screens (m)
L_2	Distance of vent with water mist screen (m)

1 Introduction

According to statistics, more than 80% of the deaths in fires are caused by smoke [1]. Smoke control is an important research content of fire science. The smoke spreading process in different forms of building space is different. As a typical building structure, narrow and long passage is not only the tie of all kinds of building space but also the only way to evacuate the crowd. The consequences cannot be imagined once the smoke gushes into the building. The common narrow and long passages in engineering include highway and railway tunnels, subway tunnels, urban underground traffic tunnels, and corridors inside buildings [2].

Fire researchers have conducted a number of scientific studies on narrow-lane fires, mainly including the migration of toxic components of smoke gas, the transport and control, of smoke and the application of water mist fire extinguishing. Huo [3] used a small-scale model experiment of 120 cm (length) * 16 cm (width) * 20 cm (height) to study the movement characteristics of hot smoke in the vicinity of the upper wall of a rectangular inclined channel under natural convection when a fire occurs in a rectangular inclined channel of finite length. Hu [4] has studied the smoke control effect of the air curtain in narrow and long passages. Yuan [5] used 1/20 small-scale model experiment to study the smoke exhaust characteristics of urban tunnel fire combined ventilation; Dong [6] used large-scale full-scale experiment to study the fire isolation effect of water curtain. The results show that the heat insulation performance of the water curtain is good, but the reason for the poor smoke prevention effect is that the water curtain is not only discontinuous water particles but also large. And the porosity of the water curtain is high. Fernandez [7], Felis [8], and Severino [9] proposed a double-stream-twin-jet (DS-TJ) method to control the longitudinal spread of smoke gas in tunnels. This method improved the air curtain, but the smoke gas was always circulated in the tunnel. If the smoke gas emission was not considered, the smoke control will lose its function. Fang [10] uses 10:1 model test and solid tunnel fire test to prove that water spray can effectively reduce tunnel temperature and prevent smoke and heat from propagating downstream. The experimental water spray pressure is 0.3 and 0.5 MPa. Formaldehyde is used as fuel without carbon black particles, and only changes in temperature parameters



Fig. 1 Cross section of the WMSTV system in operation

are analyzed by him. Water mist, as an efficient, water-saving and environmental protection fire extinguishing method, has also been applied to tunnel fires [11, 12]. Its main function is to extinguish vehicle and solid cargo fires in the tunnel. In the study of water mist fire control, scholars have observed that water mist not only has a good cooling effect but also can improve the visibility of fire field by washing dust particles [10, 13, 14].

According to the previous researches, it can be concluded that most previous studies focused on the smoke compartmentation in tunnels to improve transverse ventilation efficiency. A new smoke control system, which is composed of water mist screens and transverse ventilation system (WMSTV system) as shown in Fig. 1, was proposed by Liang [15]. The system of water mist screens was used to confine the smoke and fire in a restrained zone. The length of the restrained zone will be doubled when a fire directly below the water mist screen. Numerical method with a large eddy simulation model (LES) has been used in this research. The traditional natural ventilation system and transverse ventilation system without water assistance are used for comparison of the effectiveness WMSTV. Based on the previous study by Liang [15], the selection of key parameters for the application of WMSTV system can be optimized by simulation using FDS. Through the analysis of the visibility distribution and the extraction efficiency of every smoke vents, both the control parameters of the transverse ventilation system, including the numbers of vents and the distances between different vents, and of the water mist screen, including the distance between different screens and between the smoke vent and the screen, can be determined. The objective of this paper is to present a data set of simulation for reference when drafting codes or conducting the relative experiments.

2 Numerical Experiments

CFD has been widely used in tunnel fire researches. Fire Dynamics Simulator (FDS, Version 5.0) developed by NIST is selected for numerical simulations of thermal driven flow in this study. Previous studies have shown that FDS is an effective and reliable numerical tool for tunnel fire study.

2.1 FDS

Fire Dynamic Simulation (FDS) software has been regarded as a practical tool for simulating fire-induced environment as it solves numerically a set of the Navier–Stokes equations for thermally driven flow. It includes both direct numerical simulation (DNS) model and large eddy simulation (LES) model [14]. It is used to conduct the numerical simulation validated by an experimental test in Northeastern University, and FDS is used to numerically investigate the different droplet sizes on the fire suppression/extinguishment mechanisms [15, 16]. Lagrangian particles can be used to represent a wide variety of objects that are too small to resolve on the numerical grid. In FDS spray modeling, Lagrangian particles are used to represent water droplets. The spray characteristics are defined at the injection point by a set of parameters including the fluid thermal properties, droplet size distribution, and injection features. The droplet size distribution is denoted by Rosin–Rammler and log-normal distributions.

$$F(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma d'} e^{-\frac{[\ln(d'/d_m)]^2}{2\sigma^2}} dd' & (d \leq d_m) \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma} & (d_m < d) \end{cases} \quad (1)$$

2.2 Physical Model and Grid Sizes

The model tunnel has a rectangular cross section of 10 m (W) × 5 m (H) and a length of 600 m, as shown in Fig. 2. The height of the smoke exhaust duct is 2 m, which has the same width with the tunnel.

Grid size sensitivity studies have shown that the accuracy of the model depends on the characteristic fire diameter D^* [16], which is defined as:

$$D^* = \left(\frac{H}{\rho_0 c_p T_0 \sqrt{g}} \right)^{2/5} \quad (2)$$

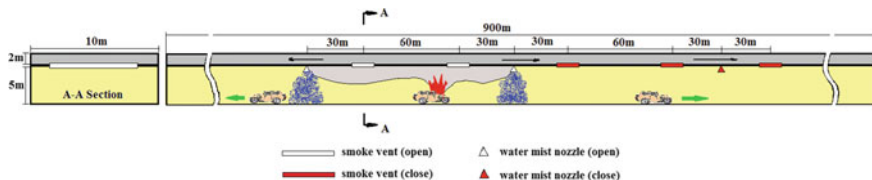


Fig. 2 Schematic diagram of the tunnel and the layout of smoke vents and water mist screens

Table 1 Computation domains and the grid number

	The domain of mesh (m)			Grid size (m)			Grid number
	x	y	z	δx	δy	δz	
Mesh 1	-5 to 5	-300 to -100	0-7.5	0.5	0.5	0.5	20 × 400 × 15
Mesh 2	-5 to 5	-100 to 100	0-7.5	0.25	0.2	0.25	40 × 1000 × 30
Mesh 3	-5 to 5	100 to 300	0-7.5	0.5	0.5	0.5	20 × 400 × 15

It is suggested that the cell size at the near field of the fire source should be 0.05–0.1D*, while the larger grid size can be used in the far field which should not exceed 0.5D* [19]. Mawhinney indicated that refining the grid size consumed more computation time without significantly improving the prediction accuracy [20]. According to NFPA 502 [21], the fire load in this study is set as 30 MW. For a 30 MW fire, D* is 3.74 m, 0.1D* is 0.34 m, and 0.5D* is 1.87 m. The computation zones with different mesh sizes are listed in Table 1.

2.3 Fire Scenarios

To investigate the parameters of WMSTV system, nine fire scenarios with different distance intervals of water mist screens and smoke vents are set. The test matrix of simulations is given in Table 2, and some typical scenarios are shown in Fig. 3. The heat release rate of fire is 30 MW. The exhaust fans are located at both ends of the smoke duct with a flow rate of 120 m³/s. The ends of the tunnel are set as an open boundary in the simulations. Both the ambient temperature is 20.0 °C. The water mist screen consists of 14 nozzles, and the layout is shown in Fig. 4. The flow rate

Table 2 Fire scenarios in numerical simulation

Scenario number	Distance of water mist screens (m)	Water mist screens position	Numbers of smoke vent	Distance of smoke vents (m)	Distance of vent with water mist (m)
1	120	-60 m/60 m	2	60	30
2			3	30	30
3			4	20	30
4	150	-75 m/75 m	2	60	45
5			3	45	30
6			4	30	30
7	180	-90 m/90 m	2	60	60
8			3	60	30
9			4	40	30

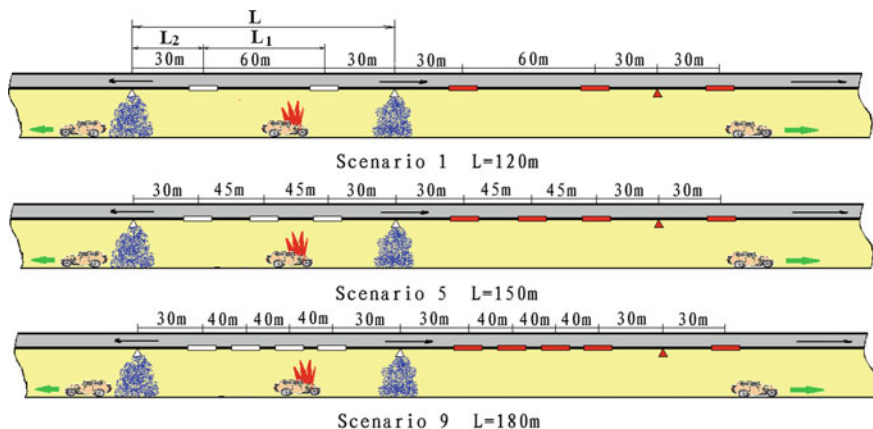


Fig. 3 Schematic diagram of the tunnel and the layout of smoke vents and water mist screens

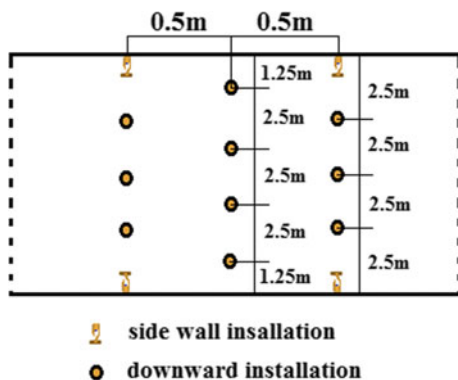


Fig. 4 Schematic diagram of the water mist nozzle arrangement

of each nozzle is 30 L/min. The initial droplet velocity is 10 m/s, and the average particle diameter is 300 μm . The injection pressure is 10 MPa. The mass flux of the water mist droplets is from 0 to 0.75 $\text{kg}/\text{m}^2/\text{s}$.

2.4 Calculation of Smoke Extraction Efficiency

The smoke extraction efficiency of the WMSTV system is defined as the percentage of the sum of the smoke extraction rate by all the smoke vents and the smoke generation rate [22]. Then, the smoke extraction efficiency for a single vent can be defined as the percentage of its smoke extraction rate by all the smoke vents and the smoke generation rate. By supposed n smoke vents were set in a WMSTV system, the

Table 3 CO₂ generation rate of diesel combustion

Heat release rate of fire source (MW)	Heat of combustion (kJ/kg)	Mass loss rate (kg/s)	CO ₂ generation rate (kg/s)
30	46,000	0.652	8.67

smoke extraction efficiency of vent *i* can be calculated as:

$$\eta_i = \frac{Q_i}{Q} \times 100\% \tag{3}$$

Therefore, the smoke extraction efficiency of the WMSTV system is:

$$\eta = \frac{\sum_i^n Q_i}{Q} \times 100\% \tag{4}$$

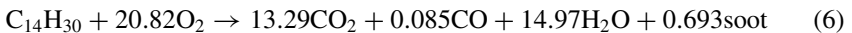
where *Q_i* is the smoke extraction rate of the single vent *i* (kg/s), and *Q* is the total smoke generation rate (kg/s).

In FDS simulation, the smoke generation rate can be replaced by the generation rate of CO₂ in the burning process, and specifying a DEVC with a ‘VOLUME FRACTION’ and a SPEC_ID of CARBON DIOXIDE will output the volume fraction of carbon dioxide in the gas phase. Thus, the smoke extraction rate for a single vent can be represented by its extraction rate of CO₂, and the smoke extraction efficiency can be expressed as:

$$\eta = \frac{\sum_i^n Q_{CO_2,i}}{Q_{CO_2}} \times 100\% \tag{5}$$

where *Q_{CO₂,i}* is the CO₂ extraction rate of the single vent *i* (kg/s), and *Q_{CO₂}* is the total CO₂ generation rate (kg/s).

Kerosene (C₁₄H₃₀) is selected as fuel in the simulation, of which the chemical reaction is:



So the CO₂ generation rate with different heat release rate can be calculated, and the results are shown in Table 3.

3 Results and Discussions

In tunnel fire scenarios, the ceiling structure of the tunnel can be easily destructed by the high temperature. And the smoke is harmful to human beings. According to Liang’s simulation [15], the decrease in visibility is the most critical factor that makes

the evacuation more difficult in a tunnel fire. For this reason, the design parameters of the WMSTV system are determined through the analysis of the factors, including the visible distance and the smoke extraction efficiency, which significantly affect the evacuation.

3.1 Visibility Distributions

The distributions of visible distance in different scenarios with the same number of smoke vents and the different distances between the water mist screens are shown in Figs. 5, 6, and 7.

As in Fig. 5, the smoke can be limited between the water mist screens in all the three scenarios with two smoke vents in every two screens, where the visible distance below 2 m high can be kept above 10 m. However, with the smoke dragged down by the water mist, the visible distance in the area between the water mist screen and the smoke vent is reduced to an unacceptable level for evacuation. And the range of this area is increased, the distance between the vent and screen also increased. According to experimental observations, the maximum moving distance for human beings is about 20–30 m away in fire smoke, for which the farthest distance from

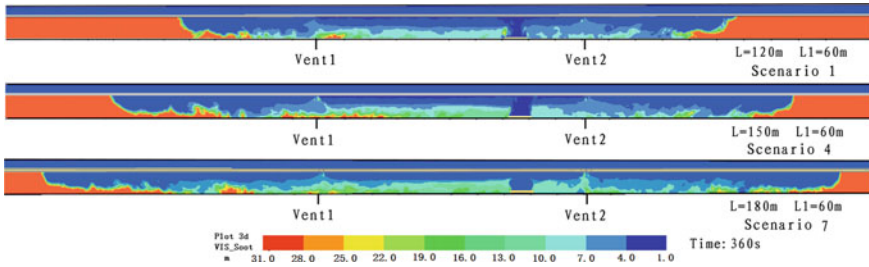


Fig. 5 Visibility distributions of two vents with different water screen distance

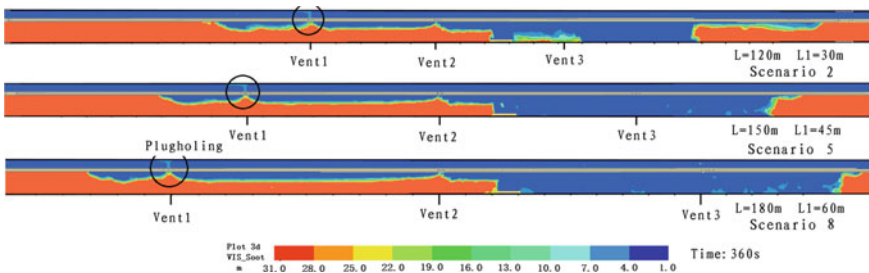


Fig. 6 Visibility distributions of three vents with different water screen distance

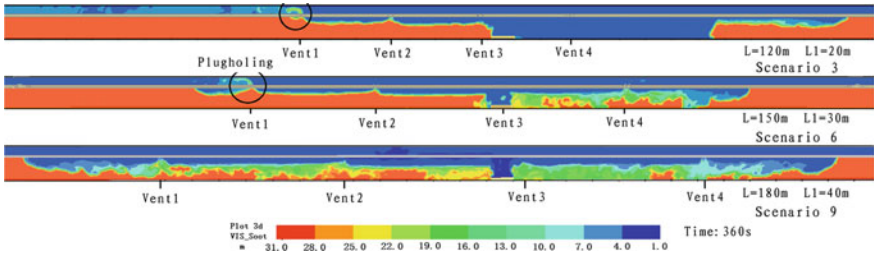


Fig. 7 Visibility distributions of four vents with different water screen distance

any location to the nearest smoke vent in the building is limited in 30 m in the Code for Fire Protection Design of Building in China. So the distance between the water mist screen and smoke vent can reasonably be 30 m.

From Fig. 6, it can be seen that the WMSTV system failed to control the smoke in the condition that three smoke vents are set between every two screens. Although the smoke diffusion distance is also limited, the visibility is reduced severely that the visible distance below 2 m high is decreased to 1 m, which is hard for evacuation and rescue operation. What's more, plugholing can be observed at the smoke vent on the left side of the fire source, which significantly reduces the smoke extraction efficiency that will be illustrated in the analysis of smoke extraction efficiency below. At the same time, the flow rate of smoke to the vent is slowed down by the extraction of fresh air in replace of smoke, which brought smoke control much more difficulty to the water mist screen on the other side.

It can be seen in Fig. 7 that, the shorter distance between smoke vents leads to the worse extraction result when the number of vents between two water mist screens is upgraded to four. In Scenario 3 where the water mist screen spacing is 120 m and the smoke vent spacing is 20 m, smoke is successfully controlled in the left side by the water mist screen throughout the duration of 360 s. But on the right side of the fire source, the smoke vents are installed too close to control the smoke effectively, in which the severe plugholing effect can be obviously observed at Vent 1. For Scenario 6 where the water screen spacing is increased to 150 m and the smoke vent spacing is increased by 10 m, smoke control effect of the WMSTV system is improved with the water mist screen on the left side closed in 360 s, but plugholing has still existed at Vent 1. While the water screen spacing is enlarged to 180 m with the smoke vent spacing increased to 40 m, the water mist screens on both sides are opened, where smoke is completely limited in the 180 m spacing through the vent extraction, and plugholing is successfully eliminated. The visibility below 2 m can be kept above 16 and 7 m, respectively, between water mist screens, which also demonstrate the better smoke extraction effectiveness.

From the analysis of scenarios with different water mist screen spacing above, it can be seen that the smoke control effectiveness is strongly affected by the number of smoke extraction vents and the spacing distance between them. It is suggested that minimum spacing distance between smoke vents should not be less than 40 m, while

the maximum spacing distance should not exceed 60 m. A suitable spacing distance between the water mist screen and smoke extraction vent in the range of 30–45 m is recommended.

3.2 *Smoke Extraction Efficiency*

In this section, the smoke extraction effect is analyzed in the view of smoke extraction efficiency. The CO₂ extraction rate for single vents and open time of the water mists screen are listed in Table 4. The calculation results for smoke extraction efficiency of both the single vent and the total WMSTV system is shown in Table 5.

From the results of the four scenarios where one smoke vent is set between water mist screens listed below, it is failed to control the smoke with the only single vent. In scenarios with the screen spacing distance of 60, 120, 150, and 180 m, the smoke extraction efficiency is 14.88, 15.69, 16.38, and 16.6%, respectively, which is too inefficient to control the smoke. Large amount of smoke spreading through the water screen on the right side is cooled and dragged down by the water mist which makes the smoke layer disturbed so severely that the tunnel space on the right side of the fire source is quickly filled with the settling smoke. On the left side of the fire source, the violent plugholing effect can be clearly observed and water mist screen on the left-hand side has not opened in 360 s.

In scenarios where two smoke vents are located between the screens, the smoke is successfully limited in the spacing between screens with the screens on both sides opened which guaranteeing the smoke separation. For this reason, the smoke can only be extracted out from the smoke vents, which greatly improved the smoke extraction efficiency that the total efficiency in Scenario 1, Scenario 4, and Scenario 7 have upgraded to 89.85, 81.11, and 82.93%, respectively. The extraction efficiency for a single vent is dependent on its distance to the fire source. The nearer distance corresponds to greater efficiency. For example, in Scenario 1 where the screen spacing is 120 m, the extraction efficiency of Vent 1 with a distance of 45 m is 27.22%, while the extraction efficiency of Vent 2 with a distance of 15 m is 62.63%.

In Scenario 2, 5, and 8, three smoke extraction vents are located in the water mist screen spacing. In Scenario 2 with a 120 m screen distance, the screen on both sides is opened. However, the total smoke extraction rate can only reach 22.45% and the single vent extraction rate is low, for the 30 m smoke vent spacing is so short that plugholing effect can be observed at both the two smoke vents on the left side. On the right side of the fire source, the water mist screen is failed to stop the smoke from spreading through. And in Scenario 5 and 8, only the screen on one side is opened, which cannot control the smoke spreading. In addition, the smoke extraction efficiencies are only 22.28 and 19.33%, respectively, in Scenario 5 and 8, which is too low to accept. Thus, none of the three scenarios should be taken into operation in engineering applications.

When the number of smoke vents is added up to four, different results occur in Scenario 3, 6, and 9. Both in Scenario 3 and 6, with the screen spacing distance, is 120

Table 4 Open time and CO₂ extraction rate at smoke vents

Scenario number	Vent 1		Vent 2		Vent 3		Vent 4		Water mist screens	
	Open time (s)	CO ₂ flow rate (kg/s)	Open time (s)	CO ₂ flow rate (kg/s)	Open time (s)	CO ₂ flow rate (kg/s)	Open time (s)	CO ₂ flow rate (kg/s)	Open time (s)	
									1	2
1	16.7	2.36	4.81	5.43					36	27.4
2	20.7	0.29	4.45	0.772	4.81	0.884			120	24.8
3	21.5	0.0813	7.7	0.378	3.34	0.713	4.82	0.757		22.9
4	16.7	2.02	4.81	5.012					56.2	42.2
5	37.4	0.279	4.45	0.806	9.26	0.847				29.2
6	51.4	0.156	11.8	0.259	4.35	1.704	13	0.56		56.6
7	4.8	1.98	16.3	5.21						82.5
8	61.1	0.165	4.81	0.816	17.8	0.695				38.9
9	42.6	1.357	13.3	2.108	5.57	2.386	23	1.423		65.9

Table 5 Smoke extraction efficiency

Scenario number	Smoke extraction efficiency (%)				Overall efficiency (%)
	Vent 1	Vent 2	Vent 3	Vent 4	
1	27.22	62.63			89.85
2	3.35	8.9	10.2		22.45
3	0.94	4.36	8.22	8.73	22.25
4	23.3	57.8			81.11
5	3.22	9.3	9.76		22.28
6	1.8	3	19.65	6.45	30.9
7	22.84	60.09			82.93
8	1.9	9.41	8.02		19.33
9	15.65	24.31	27.52	16.41	83.9

and 150 m, respectively, only the water mist screen on the right side is opened and the total smoke extraction efficiency is 22.25 and 30.90%, respectively, which seems still to be low. It is caused by the excessively short spacing distance, which is only 20 m in Scenario 3 and 30 m in Scenario 6, because not only will the control effect of water screen be decreased but also severe plugholing effect might be resulted if the spacing distance of vents gets too short. While in Scenario 9 the vent spacing distance is added up to 40 m, the smoke is successfully controlled with relatively high efficiency by the WMSTV system. Therefore, it is suggested that the number of smoke vents installed between the water screens should be dependent on the screen spacing, and the minimum distance of 40 m is recommended.

4 Conclusion

Nine scenarios of the application of WMSTV system in tunnel fire smoke control are simulated and analyzed in the view of the effectiveness and efficiency in this chapter. It can be concluded that the water mist screen spacing distance should be determined concerning the total length of the evacuation path or refuge path in tunnels, and the number of smoke vents located between the water mist screens should be determined in accordance with the screen spacing distance. The detailed conclusion can be listed as follows:

1. In the fire scenario with fire source of which heat release rate is 30 MW, the minimum spacing distance between smoke vents should not be less than 40 m, while the maximum spacing distance should not exceed 60 m.
2. The spacing distance between the screen and vent is suggested to fall in 30–45 m. Two vents are recommended in the control zone with the screen spacing of 120 and 150 m. Four vents are recommended in the control zone with the screen spacing of 180 m.

3. All the result is based on the simulation in FDS, which is still needed to be further proved by experiment.

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