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# Model tests of fire smoke control effects in highway tunnels

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Research Paper

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## Model tests of fire smoke control effects in highway tunnels

In this work, a typical tunnel 150 m in length is selected and modelled at a scale of 1:15 to assess its effects on smoke control. A total of 32 model tests on smoke flow pattern and longitudinal temperature distribution have been carried out based on the Froude similarity criterion. The results show that smoke control is affected by three factors, namely, the longitudinal airflow velocity, number of opened smoke-exhaust dampers, and fire power, out of which the longitudinal airflow velocity has the greatest effect on smoke control.

### Key words:

tunnel fire, model test, smoke, temperature distribution, control effect

Prethodno priopćenje

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## Modelska ispitivanja utjecaja na kontrolu požarnog dima u cestovnim tunelima

U radu je odabran tipičan tunel dužine 150 m te je izrađen njegov model u mjerilu 1:15 kako bi se ocijenili utjecaji na kontrolu dima. Na temelju Froudeovog kriterija sličnosti provedena su 32 modelska ispitivanja obrazaca širenja dima i uzdužne raspodjele temperatura. Rezultati pokazuju da na kontrolu dima utječu tri faktora i to brzina uzdužnog strujanja zraka, broj dimovodnih zakloпки i energija požara, pri čemu se smatra da na kontrolu dima najviše utječe brzina uzdužnog strujanja zraka.

### Ključne riječi:

tunelski požar, ispitivanje na modelu, dim, raspodjela temperature, utjecaj na kontrolu

Vorherige Mitteilung

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## Modellversuche zum Einfluss der Brandrauchbekämpfung in Straßentunneln

Ein typischer 150 m langer Tunnel wurde ausgewählt und ein Modell im Maßstab 1:15 entwickelt, um die Auswirkungen auf die Rauchkontrolle zu bewerten. Basierend auf dem Froude-Ähnlichkeitskriterium wurden 32 Modellversuche der Rauchausbreitungsmuster und der Temperaturverteilung in Längsrichtung durchgeführt. Die Ergebnisse zeigen, dass die Rauchkontrolle durch drei Faktoren beeinflusst wird, nämlich die Geschwindigkeit des Längsluftstroms, die Anzahl der Abgasventile zur Rauchableitung und die Brennenergie, wobei angesehen wird, dass die Rauchkontrolle am stärksten von der Geschwindigkeit des Längsluftstroms beeinflusst wird.

### Schlüsselwörter:

Tunnelbrand, Modellprüfung, Rauch, Temperaturverteilung, Einfluss auf die Kontrolle

## 1. Introduction

The highway tunnel construction activity in China has been rapidly developing since the 1980s, and especially as from the start of the 21st century. According to statistics, there are 16229 highway tunnels in China, with the total length of 15285.1km, including 3841 long tunnels (6599.3 km) and 902 extra-long tunnels (4013.2 km) [1]. The term "long" denotes tunnels ranging from 1000 m to 3000 m in length, while the term "extra-long" denotes tunnels of more than 3000 m in length [2]. As the number, length and density of highway tunnels is rapidly increasing, potential risks incurred by tunnel users is also increasing, with fire being the most dangerous one [2-4]. Tunnel fires cause great occupant casualties and huge economic losses, but are relatively infrequent [5-7]. Individual causes of highway tunnel fires are shown by percentage in Figure 1 [8]. In a tunnel, the space is narrow and long and the number of evacuation exits is limited. That is why, when a fire breaks out, the resulting smoke is not easy to dissipate [9-12]. The hot smoke in the tunnel can not only cause damage to the tunnel structure but can also pose a severe threat to people's lives [13-17]. The smoke can also decrease visibility in tunnels, which makes it difficult to carry out evacuation and rescue operations [18-20].

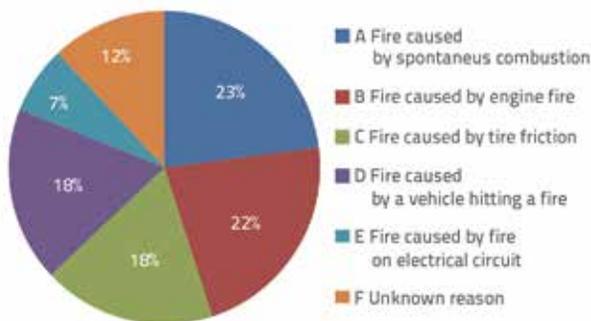


Figure 1. Causes of fire in highway tunnels [8]

Many researchers have made studies about factors that have an effect on fire smoke control in highway tunnels. Thus, Vauquelin and Megret [21] built a 1:20 tunnel model, by which they investigated the effects of both the shape and positioning of smoke-exhaust dampers on smoke control. They came to the conclusion that the dampers had no effect on exhausting fire smoke when they were opened at the top of the tunnel and had only poor exhausting effect when they were opened at the side walls of the tunnel. However, Vauquelin and Megret did not make research about longitudinal arrangement of the smoke-exhaust dampers. Ingason et al. [22] utilized a 1:23 model to investigate the effects of airflow velocity in tunnel on the following parameters: highest smoke temperature, temperature distribution, and smoke stratification. However, their study is not related to smoke-exhaust dampers. Xu et al. [23] took advantage of numerical simulations to discuss the fire-induced airflow velocity

on a centralized smoke-exhaust system. They reported that the smoke would be smoothly evacuated only if the fire-induced airflow velocity reached a certain value. However, only a single fire power was discussed in their study. Wu et al. [24] conducted a study on the effect of several parameters of a mountain tunnel that had an independent smoke-exhaust system on smoke control. Wu et al. [25] built a 1:10 model to carry out a tunnel fire test in which the heat-extraction efficiency of a centralized smoke-exhaust mode was investigated, and the effect of smoke-exhaust dampers on the heat-extraction efficiency was discussed. However, they did not study temperature distribution along the tunnel. Yi et al. [26] applied a 1:10 tunnel model to study smoke exhaust under a semi-transverse ventilation mode. Their results showed that the effect of the semi-transverse ventilation system on exhausting smoke is dependent on the number of opened smoke-exhaust dampers, the gap between the dampers, the area of a single damper, and the distance between the smoke vent and the air blower. However, their study was only related to a single fire power.

In the above studies, numerical simulations or model tests were carried out to study effects of the longitudinal airflow velocity, the smoke-exhaust dampers and the fire power on smoke control, respectively. However, there are very few studies in which the integrated effect of the three factors is discussed. In this work, a 1:15 tunnel model is built to make analysis of the temperature distribution and smoke spread in the tunnel, so as to figure out the relationship between the three factors and their effect on smoke control in highway tunnels.

## 2. Basic description of physical simulation model

### 2.1. Theoretical basis

Similarity criterion is the basis of the model test that is used to obtain reliable results. To construct the model test, the first step is to determine the way to build the model and select parameters for the test. In the model test, the fluid motion in the model is similar to that in an actual tunnel. Therefore, the kinetics of the fluid in the model must be similar to the kinetics of the fluid in the actual tunnel. In other words, the same motion parameters must be proportional, including geometric similarity, kinematic similarity, force similarity, and thermal similarity. In addition, initial conditions and boundaries must be the same. During the test, however, it is difficult to make sure that the parameters of the model are similar to the parameters of the actual tunnel. From the characteristics of tunnel fires, we know that the Froude similarity criterion is practically applicable for making model tests on smoke flow and control. Therefore, the Froude number ( $Fr$ ) is our first choice to deal with similarity. In this test, the model is designed and built at the scale of 1:15. Under the guidance of the Froude similarity criterion, the proportional relationships between the parameters of the model  $m$  and the parameters of the actual tunnel  $p$ , can be obtained as shown below:

Characteristic size:  $\frac{L_m}{L_p} = \frac{1}{15}$  (1)

Temperature:  $T_m = T_p$  (2)

Volume flow rate:  $\frac{V_m}{V_p} = \left(\frac{L_m}{L_p}\right)^2 = \left(\frac{1}{15}\right)^2$  (3)

Fire source power:  $\frac{Q_m}{Q_p} = \left(\frac{L_m}{L_p}\right)^2 = \left(\frac{1}{15}\right)^2$  (4)

Velocity:  $\frac{v_m}{v_p} = \left(\frac{L_m}{L_p}\right)^{\frac{1}{2}} = \left(\frac{1}{15}\right)^{\frac{1}{2}}$  (5)

Time:  $\frac{t_m}{t_p} = \left(\frac{L_m}{L_p}\right)^{\frac{1}{2}} = \left(\frac{1}{15}\right)^{\frac{1}{2}}$  (6)

where:

- $T$  - temperature [°C]
- $L$  - feature size [m]
- $V$  - volume flow rate [m³/s]
- $Q$  - fire power [kW]
- $v$  - velocity [m/s]
- $t$  - time [s].

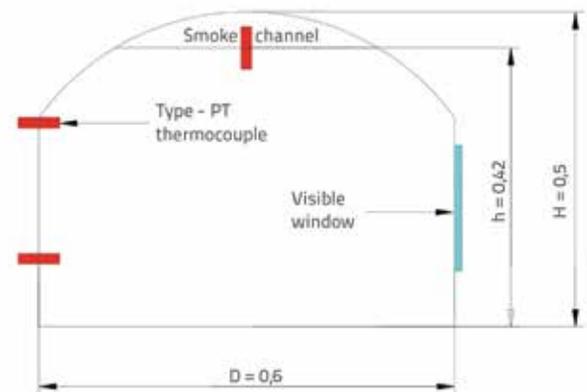
### 2.2. Tunnel model

In this work, the model is built on the basis of an actual tunnel in Caihongling Mountain, Jiangmen city, Guangdong province. The actual tunnel is 5.068 km long, 9.5 m wide and 6.2 m high. A typical section 150 m in length was selected as the object of the study. The typical section was then modelled at the scale of 1:15, Figure 2. The model is composed of 10 sections that are all made of galvanized iron sheets, Figure 3. Each section is 1 m long, 0.6 m wide and 0.4 m high, Figure 4. The model is put on a horizontal level. From the 2<sup>nd</sup> section to the 9<sup>th</sup> section, there is a window at the side of each section for the purpose of observing the fire in the tunnel. In the test there are four cases, i.e. 0, 1, 2

and 3. Smoke-exhaust dampers are opened respectively in each case, as shown in Figures 5.a and 5.b.



Slika 3. Tunnel model



Slika 4. Cross-sectional view of the tunnel model

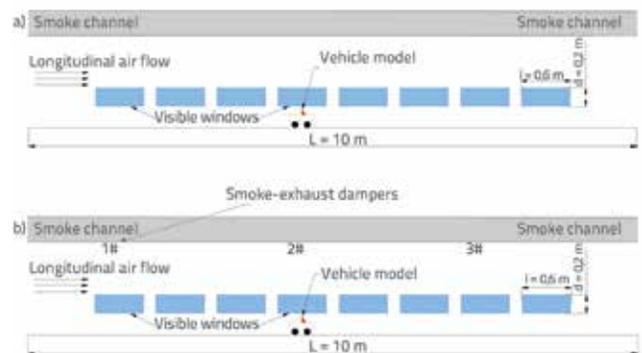


Figure 5a. Longitudinal sections of the tunnel with different numbers of opened smoke-exhaust dampers: a) without opening; b) first smoke-exhaust damper open

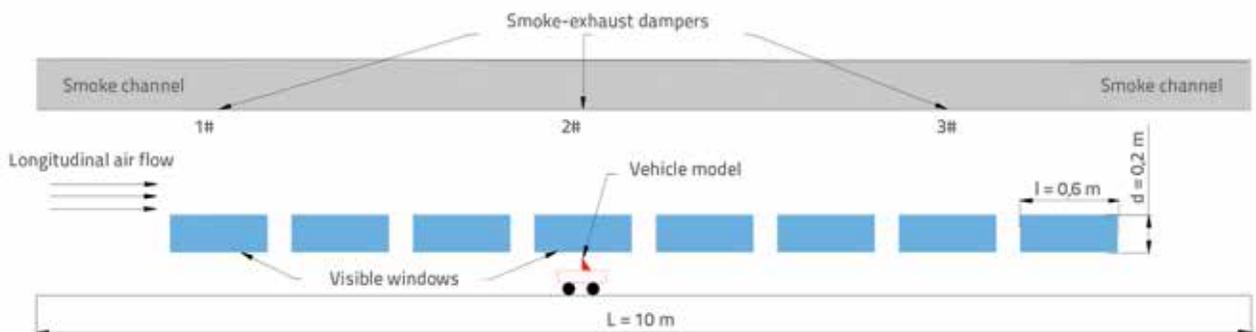


Figure 2. Sectional view of the tunnel model

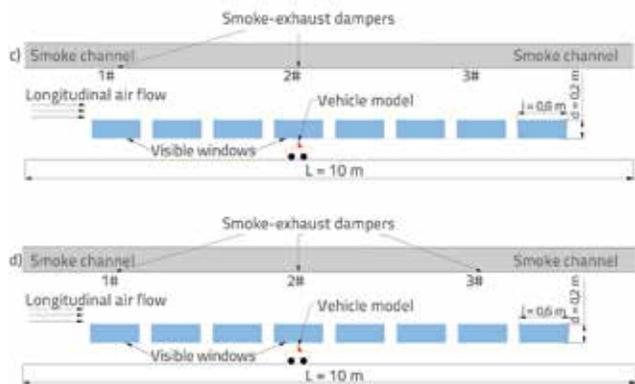


Figure 5b. Longitudinal sections of the tunnel with different numbers of opened smoke-exhaust dampers: c) second smoke-exhaust damper open; d) third smoke-exhaust damper open

### 2.3. Fire source

In the test, kerosene is used as the fire source to simulate the fire in the tunnel model. The kerosene and some paper scraps are put in a steel container. The paper scraps are used to generate smoke. The steel container is 0.15 m long and 0.12 m wide, i.e. the container measures 0.018 m<sup>2</sup> in area. There are three oil grooves in the container, and the area of each groove is 0.006 m<sup>2</sup>. Therefore, various fire powers can be simulated by changing the amount of fuel and the burning area. With reference to the standard by PIARC (Permanent International Association of Road Congresses) [30], we have set the fire powers for various vehicle models, as shown in Table 1.

Most vehicles in a tunnel are cars and trucks. Therefore, fire powers are determined in this test by reference to cars and trucks. In the experiment, geometric dimensions of the burning vehicle model are carefully designed. The model vehicle is 0.15 m in length by 0.12 m in width and the surface area is 0.018 m<sup>2</sup>. The fuel-filling part of the vehicle is divided into three oil tanks, each of which is 0.006 m<sup>2</sup>. The heat release is adjusted by the amount of fuel (ethanol) and by the change in the burning area. According

to the *Fr* similarity criterion, the fire power of the model vehicle is set to 17.2 kW (corresponding to 15 MW in a real fire accident) for single vehicles/cars and the fire power of 22 kW (corresponding to 20 MW in a real fire accident) is set for coaches/buses. As listed in Table 1, the design fire of 15 MW in tunnel is based on the assumption of fire development in a single vehicle or of multiple cars being involved in a collision. The fire power is classified into two grades: A and B. Grade A: the kerosene is put into two oil grooves; each groove contains 20 ml of fuel and 10 g of wood; and the fire power is about 17.2 kW. Grade B: the kerosene is put into three oil grooves; each groove contains 20 ml of fuel and 10 g of wood; and the fire power is about 22 kW, as shown in Figure 6.



Figure 6. burning vehicle model

### 2.4. Air blower and data collection system

In the test, a low-noise tubular air blower (model: SFG) is used to generate longitudinal airflow. The blower is equipped with a regulator to regulate velocity of airflow. According to the data in the *Code For Design of Road Tunnel* (JTG D70/2-2014), the longitudinal ventilation velocity of more than 2.5m/s (obtained from [31]) and of no more than 12m/s (obtained from [28]) is recommended for a single way tunnel. The velocity of the airflow generated by the blower should be controlled in the range of 0 ≈ 1 m/s. Therefore, four velocities are set in this test: 0 m/s, 0.3 m/s (corresponding to 1.16 m/s in reality), 0.6 m/s (corresponding to 2.32 m/s in reality) and 0.9 m/s (corresponding to 3.48 m/s in reality).

An automatic data collection system that consists of a high-precision multichannel temperature inspection instrument (brand: Applent; model: WT-500) is used in the test to collect the data every four seconds. The type-K thermocouples that can measure temperature from 0 °C to 1000 °C are mounted on horizontal sections L1 and L2, while the type-PT thermocouple

Table 1. Typical peak HRRs (Heat Release Rates) for various road vehicles [30]

Vehicle model	Passenger Car	Light duty vehicle	Coach, Bus	Lorry, HGV up to 25 tons	HGV typically 25-30 tons	Petrol tanker
Peak HRR, MW	5-10	15	20	30-50	70-150	200-300

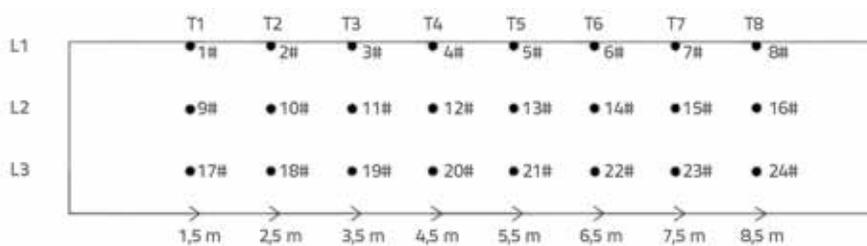


Figure 7. Distribution of temperature measurement points

that can measure temperature from 0 °C to 500 °C is mounted on horizontal section L3. T1 represents the vertical section that is 1.5 m distant from the entry of the tunnel, while T2, T3, T4, T5, T6, T7 and T8 represent vertical sections that are 1m distant from each other. L1 represents the horizontal plane at the top of the tunnel. L2 represents the horizontal plane that is 0.15 m away from the top of the tunnel. L3 represents the horizontal plane that is 0.13 m away from the bottom of the tunnel. The temperature is then measured at the 24 intersections of the 8 vertical sections and the 3 horizontal planes, as shown in Figure 7.

## 2.5. Test conditions

A total of 32 model tests have been performed under various conditions. The information about the number of opened smoke-exhaust dampers, airflow velocity, and fire power, is given in Table 2.

Table 2. Model test conditions

Code	Fire source power [kW]	The numbers of smoke-exhaust dampers	Ventilation velocity [m/s]
A01	17.2	0	0; 0.3; 0.6; 0.9
A02	17.2	1	0; 0.3; 0.6; 0.9
A03	17.2	2	0; 0.3; 0.6; 0.9
A04	17.2	3	0; 0.3; 0.6; 0.9
B01	22	0	0; 0.3; 0.6; 0.9
B02	22	1	0; 0.3; 0.6; 0.9
B03	22	2	0; 0.3; 0.6; 0.9
B04	22	3	0; 0.3; 0.6; 0.9

## 2.6. Smoke-dampers

Smoke-exhaust dampers are used in these experiments to simulate ventilation of exhausting smoke when the fire breaks out. A total of 3 dampers are set up in the experimental tunnel model. Such dampers are situated at 2.5 m, 4.5 m and 6.5 m away from the tunnel edge (Referring to Figure 2, from left to right). The damper power is 0.09 kW and the rotation speed is 1450 r/min, which can generate the airflow quantity of 100 m<sup>3</sup>/h. Exhaust damper dimensions are set to 0.1 m × 0.1 m for ventilation reasons.

## 3. Test results and discussions

### 3.1. Smoke distribution in tunnel with smoke-exhaust dampers opened, with no longitudinal airflow

When there is no longitudinal airflow, the opened smoke-exhaust dampers have great effect on both the distribution and temperature of smoke in the tunnel. When the smoke-exhaust dampers are not opened, the smoke plume develops

symmetrically and the temperature in the tunnel distributes sideward, uniformly and symmetrically around the fire source. In addition, the tunnel is full of smoke, which is not good for the occupant and vehicle evacuation and makes it difficult for rescuers to enter the tunnel.

When the smoke-exhaust dampers are opened, there is a pressure difference in the tunnel, under which the smoke becomes thinner and spreads more quickly towards the dampers, and the smoke stratification is formed in the tunnel, which relieves the stress with regard to personal evacuation and rescue works. When only damper 1 is opened, the smoke around damper 1 becomes thinner, but the thickness on the other side does not change greatly. When dampers 1 and 2 are opened, the thickness of the smoke on both sides decreases greatly, especially at the upstream of damper 1. When dampers 1, 2, and 3 are opened, the exhausting effect is further improved and the smoke becomes very thin, thus diminishing the threat to the safety of persons and vehicles. Smoke distribution in tunnel when different numbers of smoke-exhaust dampers are opened is shown in Figure 8.

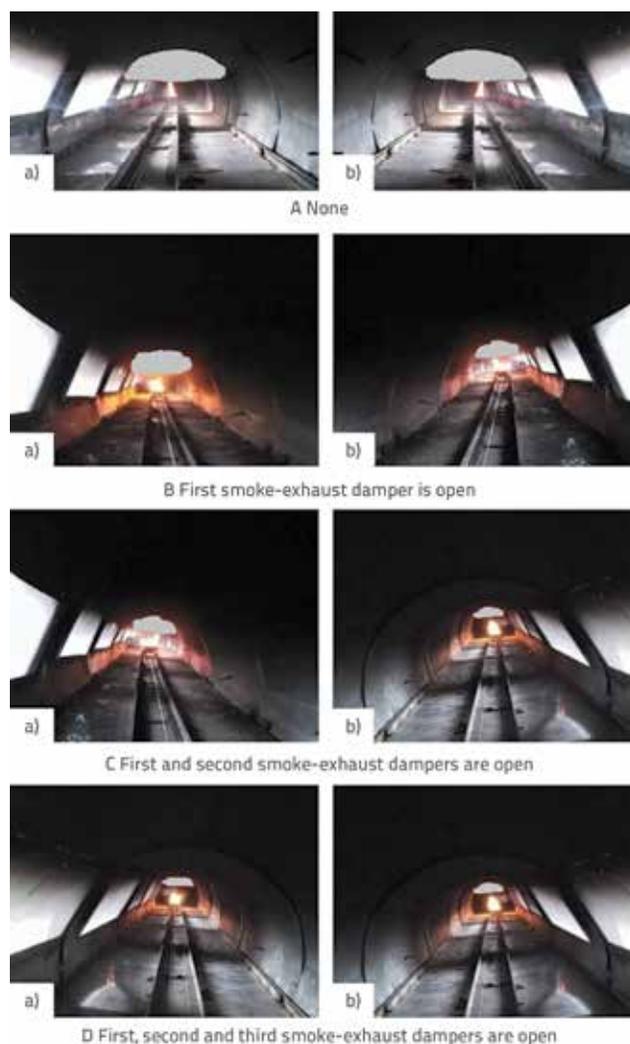


Figure 8. Smoke distribution in tunnel when different numbers of smoke-exhaust dampers are opened: a) View from upstream; b) View from the downstream

### 3.2. Effects of airflow velocity and number of opened smoke-exhaust dampers on temperature in tunnel

Figures 9 through 12 show temperature distribution at L1, L2, and L3 under different conditions, where the ordinate represents the temperature, and the abscissa represents the distance to the fire source. Figure 9 shows the longitudinal temperature distribution in tunnel without airflow, while Figures 10, 11, and 12 show temperature distribution comparisons corresponding to different airflow velocities in segment L1 (Figure 10), in segment L2 (figure 11) and in segment L3 (Figure 12).

When there is no airflow and when no smoke-exhaust dampers are opened, the temperature at L1, L2 and L3 is symmetrically distributed around the fire source, and the highest temperature increases with fire power. The temperature at L2 is lower than the temperature at L1, and the biggest drop is about 200 °C-400 °C (i.e., lower by 50 %). The temperature at L3 is lower than the temperature at L2, and the biggest drop is about 150 °C-200 °C (i.e., lower by 65 %). When smoke-exhaust dampers are opened, the symmetrical temperature distribution in the tunnel is affected by the dampers and the highest temperatures at L1, L2 and L3 become lower accordingly.

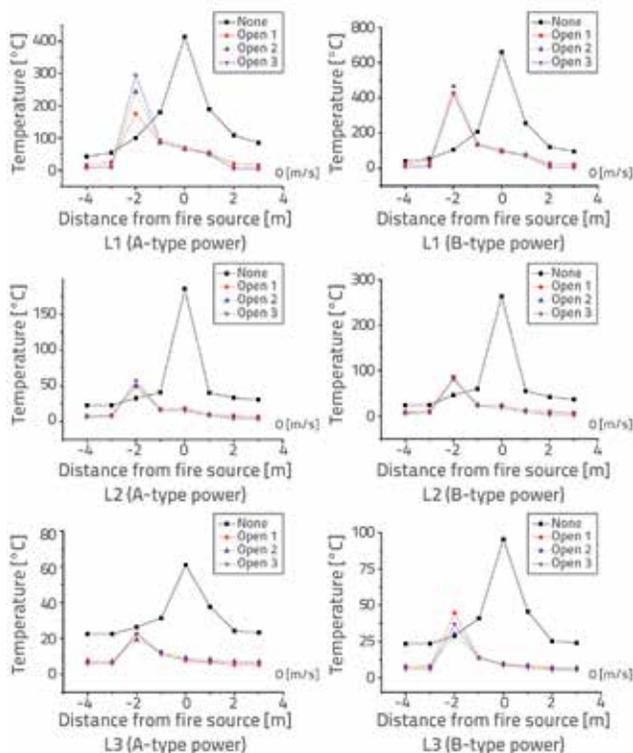


Figure 9. Longitudinal temperature distribution in tunnel without airflow

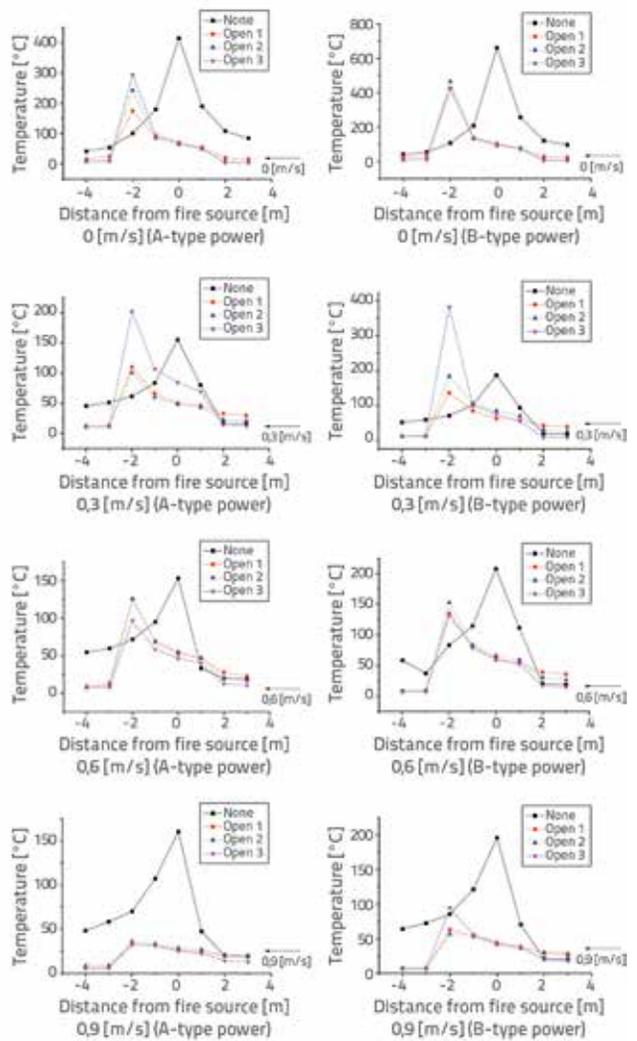


Figure 10. Longitudinal temperature distributions corresponding to different airflow velocities at L1

When no smoke-exhaust dampers are opened, the temperature of smoke in the tunnel decreases with an increase in airflow velocity, but the decreasing rate is getting lower. The temperature at the upstream of the airflow decreases more quickly than the temperature at the downstream of the airflow, which means that the position of the highest temperature is shifting towards the downstream. The effect of smoke in the upstream section of the tunnel is relatively small, while the downstream section of the tunnel is full of smoke that is exhausted through the exit. Therefore, when the fire breaks out, people in the upstream section of the tunnel should escape from the dangerous area as soon as possible.

When the smoke-exhaust dampers are opened, the distance of longitudinal flow of smoke can be greatly shortened; the smoke can be controlled within a certain range around the fire source; and most of the smoke can be exhausted through the dampers. In addition, the position of the highest temperature

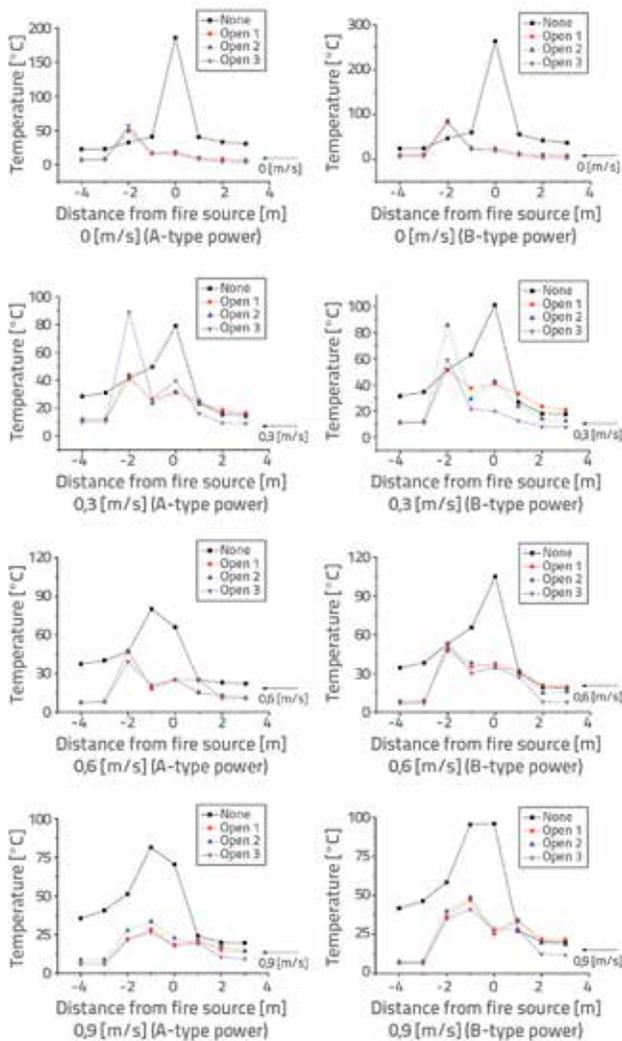


Figure 11. Longitudinal temperature distributions corresponding to different airflow velocities at L2

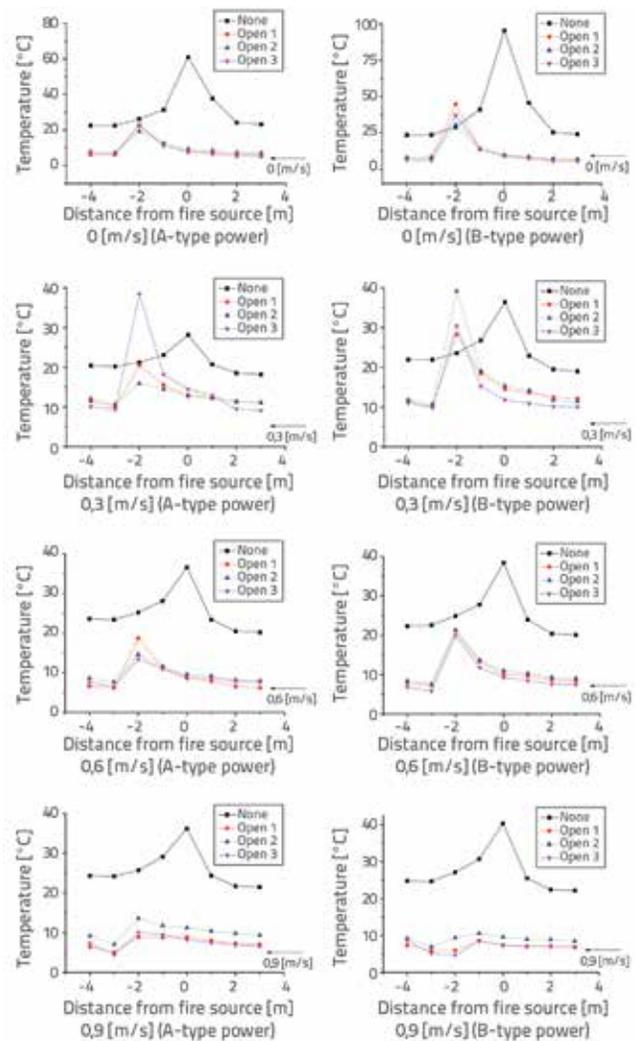


Figure 12. Longitudinal temperature distributions corresponding to different airflow velocities at L3

is shifting towards the downstream, and a large portion of smoke is exhausted from the dampers at the downstream side. When the airflow velocity is 0.3 m/s, the highest temperature at L1 is higher than that when no smoke-exhaust dampers are opened. This is because smoke turbulence will be formed under the effect of a relatively higher airflow velocity and the in-time supply of fresh air and the exhaust of the smoke will promote combustion of the fuel. When the velocity of the longitudinal airflow is high, the heat in the tunnel will be taken away along with the airflow. In this case, the difference between the temperatures corresponding to different numbers of the opened smoke-exhaust dampers becomes small.

### 3.3. Distribution of highest temperatures

For different numbers of opened smoke-exhaust dampers and fire power, the temperature distribution during the period from the start to the end of fire can be further investigated by means of the distribution of highest temperatures. Table 3 shows the distribution of highest temperatures under different conditions.

In order to present the change and distribution of temperature in the tunnel more clearly (Figures 13, 14 and 15), a line chart of the highest temperatures is plotted at different source levels according to the data given in Table 3.

Table 3. Distributions of highest temperatures under different conditions

Height type	Airflow velocities [m/s]	Fire scale	Number of smoke-exhaust dampers			
			0	1	2	3
L1	0.0	A	414.2 °C	175.2 °C	243.2 °C	293.6 °C
		B	660.9 °C	426.5 °C	465.9 °C	423.3 °C
L2		A	185.6 °C	49.3 °C	50.2 °C	57.1 °C
		B	263.4 °C	86.2 °C	84.3 °C	80.9 °C
L3		A	61.2 °C	22.3 °C	19.2 °C	22.8 °C
		B	101.1 °C	44.7 °C	30.3 °C	36.9 °C
L1	0.3	A	155.2 °C	110.3 °C	100.7 °C	202.1 °C
		B	186.3 °C	135.7 °C	183.6 °C	381.8 °C
L2		A	79 °C	41.9 °C	43.8 °C	88.9 °C
		B	102.1 °C	51.1 °C	85.7 °C	59.2 °C
L3		A	28.1 °C	20.5 °C	15.9 °C	38.4 °C
		B	36.5 °C	28.2 °C	39.2 °C	30.4 °C
L1	0.6	A	153 °C	125.1 °C	125.7 °C	96.7 °C
		B	212.9 °C	132.8 °C	152.8 °C	135.9 °C
L2		A	80.9 °C	47 °C	48.5 °C	36.3 °C
		B	111.7 °C	47.3 °C	51.7 °C	53.6 °C
L3		A	37.2 °C	18.7 °C	14.6 °C	13.4 °C
		B	38.4 °C	21.2 °C	21.3 °C	19.9 °C
L1	0.9	A	159.9 °C	32.9 °C	35.5 °C	33.5 °C
		B	195.7 °C	63.1 °C	56.4 °C	94.2 °C
L2		A	81.4 °C	28.3 °C	33.5 °C	26.9 °C
		B	96.8 °C	46.9 °C	48.8 °C	40.9 °C
L3		A	38.8 °C	8.9 °C	13.6 °C	10.1 °C
		B	40.3 °C	20.4 °C	22 °C	19.6 °C

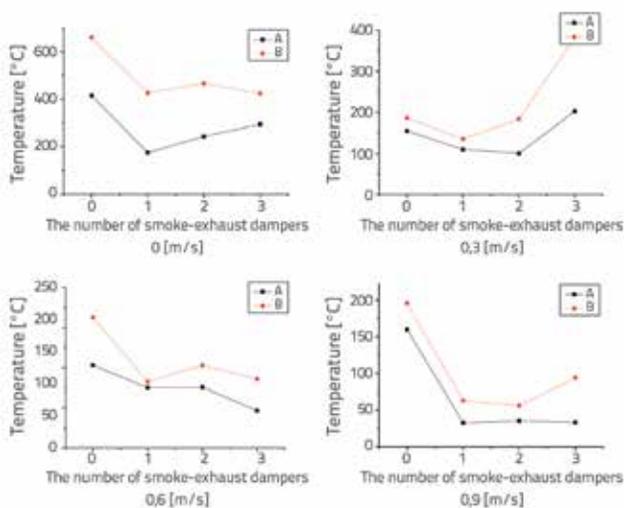


Figure 13. The highest temperature at L1

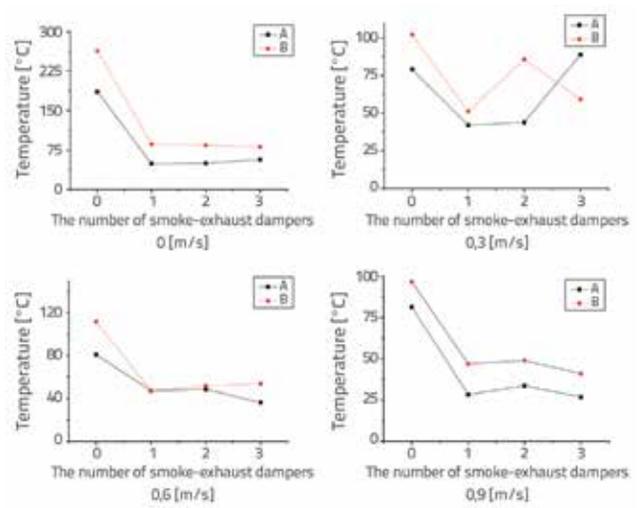


Figure 14. The highest temperature at L2

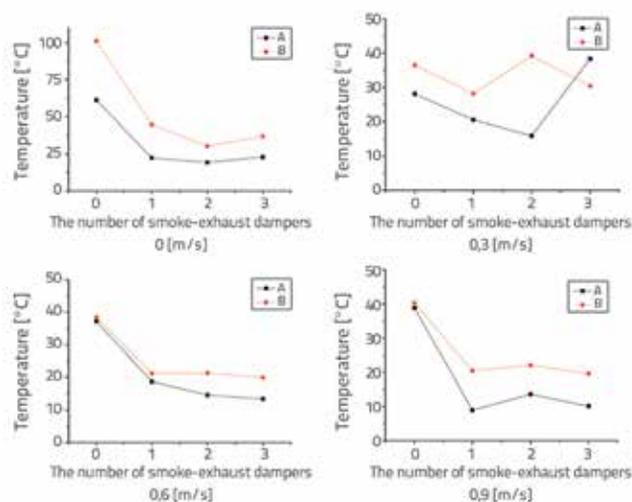


Figure 15. The highest temperature at L3

The airflow has a better effect on the exhaust of smoke in the tunnel after its velocity reaches 0.3 m/s. The decrease of highest temperatures at L1, L2 and L3 reduces with an increase in airflow velocity. Besides, the opening of the smoke-exhaust dampers plays a great role in exhausting smoke and decreasing temperature. The opening of the smoke-exhaust dampers is helpful for the evacuation of persons and vehicles, and for entry of rescuers into the tunnel. This will cut the loss caused by hot smoke.

The highest temperature at L3, which is 40 °C or so, is by about 20-50 °C lower than the highest temperature at L2. On the whole, the temperature at L3 is lower than the temperatures at L1 and L2 and fluctuates at a relatively small rate (about 10 °C) when 1-3 smoke-exhaust dampers are opened, which implies that the heat in the upper space is exhausted under the effect of the jet flow at the top of the tunnel. When a fire breaks out, the highest temperature is at the top of the tunnel and the temperature in the bottom space is relatively lower. Therefore, people should escape through the safe zone of the tunnel to keep away from high temperatures and to inhale less smoke.

#### 4. Numerical simulation for critical velocity

##### 4.1. Numerical model

The numerical simulation model is established based on the real tunnel, i.e. Caihongling Tunnel in China. The Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) program, is used to model the fire-driven fluid flow. It is 9.5 m wide (Y direction) and 6.2 m high (Z direction). The tunnel length is 150m (X direction). In the simulation, the initial temperature of the environment is 20 °C, the wall property of the tunnel is set as CONCRETE, and the section tunnel X = 0 m is set as SUPPLY. The ventilation velocity can

be changed according to experimental requirements. The section X = 150 m is set as OPEN, i.e. it is connected with the external atmospheric pressure and can be affected by natural ventilation. The grade of the tunnel is set as 0 % in the numerical model.

##### 4.2. Fire power and ventilation

The distance of smoke flowing to the left end of tunnel decreases gradually with an increase in ventilation velocity. In order to explore critical velocity of tunnel smoke without backflow, this section adopts the method of continuous adjustment of the longitudinal ventilation velocity under a certain fire power to test the relationship between fire power and critical velocity one by one. Numerical simulations of different ventilation velocities under five fire powers are carried out. Five powers are 5 MW, 10 MW, 15 MW, 17 MW, and 20 MW, respectively.

Table 4. Fire powers and longitudinal air velocities set in numerical models

No.	Fire power [MW]	Velocity [m/s]
1	5	1.5; 1.7; 1.8; 1.9; 2.0; 2.1; 2.15
2	10	2.1; 2.4; 2.7; 3.0; 3.2; 3.4; 3.45
3	15	3.0; 3.4; 3.5; 3.7; 3.9; 4.0; 4.1
4	17	3.2; 3.5; 3.7; 3.8; 4.1; 4.2; 4.25
5	20	0; 1.16; 2.33; 3.5; 3.8; 4.3; 4.35

##### 4.3. Analyses for critical velocities

Figure 16 shows that the backflow distance of smoke is large when the longitudinal ventilation velocity is small. The backflow distance of smoke decreases with an increase of longitudinal velocity. The smoke return distance decreases with an increase in ventilation velocity.

Critical velocities of fire power can roughly be determined, i.e. in the case of 5 MW, 10 MW, 15 MW, 17 MW and 20 MW, the velocities roughly amount to 2.15 m/s, 3.45 m/s, 4.1 m/s, 4.25 m/s and 4.3 m/s, respectively. The regression equation between the power of fire and critical velocity is shown as Eq. (7).

$$P = 1,6372\ln(V) - 0,4163 \tag{7}$$

where  $P$  is the fire power and  $V$  is the critical velocity of ventilation. The  $R^2$  value for this regression equation is 0.9878. When fire power increases from 5 MW to 10 MW, the critical velocity increases rapidly. The critical velocity increases slowly with an increase in power. When the power of fire source exceeds 15 MW, the critical velocity tends to be stable and the range of change is not considerable.

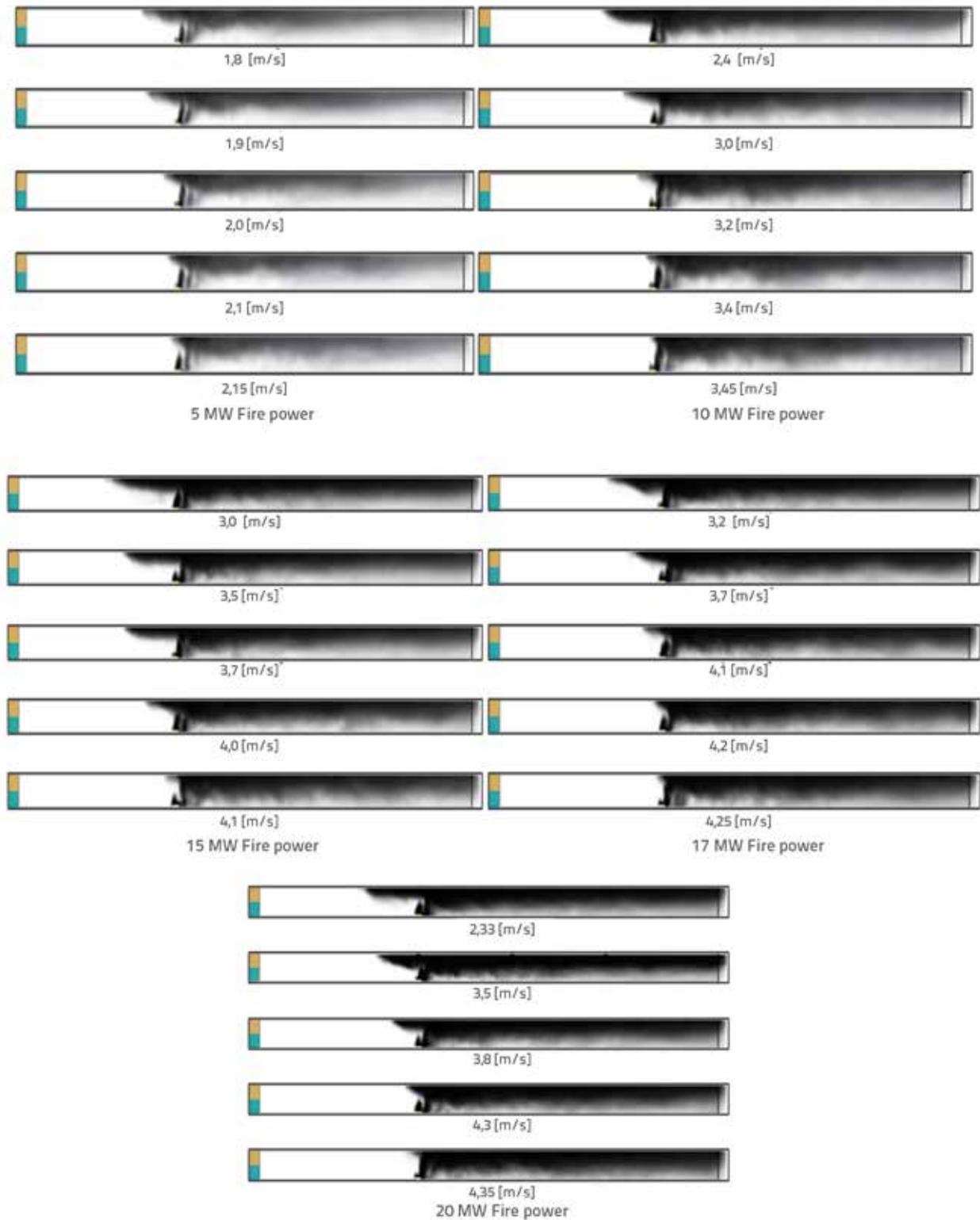


Figure 16. Smoke spread under different ventilation velocities/fire powers

## 5. Conclusions

A number of tests have been carried out in this study based on the 1:15 tunnel model to improve knowledge about the effect on smoke control in highway tunnels and to reveal the pattern and range of distribution of temperature and smoke in tunnels. The analysis involved determination of: smoke distribution in the tunnel with smoke-exhaust dampers opened when there is no longitudinal airflow, the effects of airflow velocity and the number of opened smoke-exhaust dampers on the temperature in the tunnel, and distribution of the highest temperatures. Based on this analysis, the following conclusions were made:

- Smoke control in tunnels can be affected by three factors: longitudinal airflow velocity, number of opened smoke-exhaust dampers, and fire power. Out of these factors, the longitudinal airflow velocity has the greatest effect on smoke control. Both the smoke flow and temperature distribution in tunnels can be affected by changing one of the three factors. However, it would not be economically reasonable for both smoke control and tunnel construction to consider one factor only. Therefore, all the three factors should be taken into consideration for enhancing the smoke control effect.
- When no smoke-exhaust dampers are opened and there is no longitudinal airflow, the smoke plume develops symmetrically, the temperature distributes symmetrically and becomes lower away from the fire source. When the smoke-exhaust dampers are opened, the smoke becomes thinner and spreads more quickly towards the dampers, the temperature decreases greatly, and smoke stratification is formed in the tunnel.
- The longitudinal airflow can effectively restrain temperature in the upstream section. After the airflow velocity reaches a certain value, the smoke has almost no effect in the upstream section. In addition, the temperature near the fire

source becomes lower with an increase in airflow velocity. What's more, the higher the longitudinal airflow velocity, the lower the temperature at the top of the tunnel.

- When there is longitudinal airflow and smoke-exhaust dampers are opened, the temperature at L3 is lower than 40 °C and the temperatures at L1 and L2 are lower than 100 °C, which implies that smoke-exhaust dampers are very useful when performing any emergency ventilation. Moreover, critical velocities for various fire powers, namely 5 MW, 10 MW, 15 MW, 17 MW and 20 MW, are studied through numerical simulations. The critical velocities amount to approximately 4.1 m/s and 4.3 m/s for fire powers of 15 MW and 20 MW, respectively. Roughly, the critical velocities determined by experimental results range from 0.6 to 0.9 m/s (2.32-3.48 m/s in reality). The observed differences between numerical values and experimental results could be induced by experimental conditions. They are however still quite reliable and important for firefighting phase during fire accidents.

A simple and practical model of a highway tunnel for fire testing has been built in the scope of this study, as based on the Froude similarity criterion. This paper is not only instructional, i.e. its purpose is not only to present a study of the joint effect of airflow velocity, smoke-exhaust dampers and fire power, but it can also be used as a reference for setting the parameters of smoke-exhaust dampers in tunnels.

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