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Study of the critical velocity in tunnels with longitudinal ventilation and spray systems

Z. Tang, Y.J. Liu, J.P. Yuan, Z. Fang*

Wuhan University - School of Civil Engineering, Wuhan, China

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ABSTRACT

Based on the Froude similarity law, a small-scale tunnel model (1/14) was built based in this study to investigate critical velocities of tunnels. Critical velocity is the minimum air velocity required to resist the spread of smoke from a fire upstream in a tunnel. A set of experiments was conducted to investigate the critical velocities under different experimental conditions by varying the heat release rate of the fire, ambient temperature, operating pressure and arrangement of the nozzles. The results of the tests with no spray indicated that the ambient temperature has little impact on the critical velocity. Moreover, based on the dimensionless analysis method, a new correlation was established to predict the critical velocities in the tunnel without Water spray-based Fixed Fire Fighting Systems (WFFFS). The accuracy of the correlation was illustrated by the results of the present tests and a number of tests on different scales published by other scholars. Furthermore, 60 tests with WFFFS activation were carried out. The results show that the critical velocity is significantly reduced after the water spray discharged from the nozzles. The maximum reduction of the critical velocity is approximately 31%. The reduction of the critical velocity strongly depends on the number, positions and operating pressures of the nozzles. The mechanisms of the reduction of the critical velocity caused by spraying were discussed. The cooling effect of the water droplets on hot gas is not the only mechanism for decreasing the critical velocity caused by spraying. Spraying increases the inertial force of the longitudinal airflow and is the other mechanism for the reduction.

1. Introduction

Critical velocity is the minimum longitudinal air flow velocity required to prevent fire smoke backlayering in tunnels, so the determination of this value is one of the most important design parameter for a tunnel ventilation system. There have been many theoretical models established for predicting tunnel critical velocities under various conditions. The models were developed based on two main approaches. One approach is deriving the models by applying Froude number preservation combined with some experimental data [1–4]. The earliest application of this approach was proposed by Thomas [1]. A modified Froude number was used to determine the occurrence of fire smoke backlayering. Then, the most popular models were proposed by Heselden [2] and Danziger and Kennedy [3]. Heselden suggested that the critical velocity varies with the cube root of the heat release rate in a tunnel fire, which agreed with many other studies [2]. However, some test results showed that the critical velocity becomes independent of the fire heat release rate when the scale of the fire is large enough [5–7]. Therefore, the limitation of this approach is apparent. The other approach is based on dimensionless analysis of the experimental data. Based on this approach, Oka and Atkinson [8], Wu and Bakar [9] and Lee et al. [10] proposed their own respective theoretical models. Oka and Atkinson studied the smoke movement systematically with a 1/10 reduced-scale of a colliery tunnel [8]. Compared to the study by Oka and Atkinson, the experiments conducted by Wu and Bakar considered the tunnel geometry [9]. Lee further carried out small scale experiments to consider the influence of the tunnel aspect ratio on the critical velocity [10]. Apart from these influential factors, some scholars also demonstrated that the critical velocity of the tunnels depends on the tunnel slope [11,12], vehicular blockage [8], fire location [13] and width and elevation of the fire source [13,14]. However, to the best of our knowledge, the elevation of the fire source was not a variable in any prediction model or correlation. Tilley et al. [14], in a car park study, clearly indicated that the height difference between the fire source and ceiling should be a parameter in the equation for critical velocity instead of the height of the car park. As the phenomenon of the car park fire studied in [14] is similar with the longitudinal ventilation in tunnels highlighted in [14],

* Corresponding author at: Wuhan University, School of Civil Engineering, Wuhan, China. Tel.: +86 2768772312.
E-mail addresses: zhi.tang@whu.edu.cn (Z. Tang), zfang@whu.edu.cn (Z. Fang).

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Table 1
A list of scaling law for the model tunnel.

Type of unit	Scaling model[a,b]	Eq. number
Heat Release Rate (HRR) Q (kW)	$\frac{Q_m}{Q_f} = C_L^{\frac{5}{2}}$	(1)
Time t (s)	$\frac{t_m}{t_f} = C_L^{\frac{1}{2}}$	(2)
Temperature T (K)	$\frac{T_m}{T_f} = 1$	(3)
Velocity V (m/s)	$\frac{v_m}{v_f} = C_L^{\frac{1}{2}}$	(4)
Water Flow Rate q (L/s)	$\frac{q_m}{q_f} = C_L^{\frac{5}{2}}$	(5)
Water Droplet Diameter $d(\mu m)$	$\frac{d_m}{d_f} = C_L^{\frac{1}{2}}$	(6)

[a] Index f to the full scale and index m is related to the model scale.
[b] C_L presents the ratio of the model tunnel and large-scale tunnel.

Table 2
Properties of the spraying nozzles.

Operating pressure (MPa)	Water flow rate on the small scale (L/s)	Water flow rate on the full scale (L/s)
0.1	0.007	5.1
0.2	0.010	7.3
0.3	0.012	8.8
0.4	0.014	10.3

this point should also be valid for the critical velocity study of tunnels.

WFFFS has been used as the normal fire protection system in important tunnels in Australia and Japan for a long period of time. Recently, an increasing number of other countries are reconsidering WFFFS as an efficient system for enhancing tunnel fire safety after the large range of fire catastrophes in last century. Obviously, the water spray could have a significant impact on the critical velocity in the tunnel due to the interactions among water droplets, air flow and fire smoke. However, studies of the influence of water spray on the critical velocity are not commonly found. To date, Full-scale tunnel suppression experiments were conducted by Ko and Hadjisophocleous [15], in which the tunnel was equipped with a sprinkler system to study the interaction of water spray and longitudinal ventilation, and a approach was proposed to estimate the degree of backlayering by the effect of the WFFFS. However, the water spray density is the only variation in the method used to consider the impact of a WFFFS on the critical velocity. Therefore, it is interesting to investigate the other possible influential factors of the WFFFS on the critical velocity by means of experiments.

In the present paper, sets of small-scale tunnel fire experiments were conducted. A theoretical correlation for predicting the critical velocity of the tunnel without WFFFS was developed based on the dimensional results of the tests without spray. The accuracy of the correlation is illustrated by comparison to many published tests. Then, the tendencies of the critical velocity to vary under various spray conditions were analysed. The influential factors of WFFFS for the critical velocity were highlighted. The mechanisms for the critical velocity change under the conditions of spray were ultimately discussed.

2. Scale law

Froude scaling as shown in Table 1, which has been used widely in small-scale fire research [16–21], is considered in this study. To preserve the Froude number and avoid producing laminar flow in the model tunnel, the scaling ratio should be controlled to be larger than approximately 1:20 so that the scale ratio of the tunnel model built in this work is 1:14.

3. Description of the experiments

A tunnel model was built on the scale of 1:14 based on the Froude similarity law. The schematic diagram of the tunnel model is shown in Fig. 1. The width and height of the tunnel were 930 mm and 400 mm, respectively, which represents a full-scale tunnel with a 13 m×5.6 m cross-section according to the Froude scale law. The model tunnel was 19 m long and was formed of a 10-mm thick fire resistant glaze. To avoid heat damage to the tunnel model, the section of the tunnel model in the fire source vicinity was composed of steel that was 1.25 mm thick.

Propane gas was used as the fuel. The flow rate of the fuel was metered via a rotameter and varied between 400–2500 L/h, producing fires of 9.3–58.3 kW. A porous bed burner was used as the fire source, with its top surface set flush at 205 mm above the tunnel floor. The dimension of the burner was 240 mm×270 mm, and the long side was set across the tunnel width. According to the Froude scale law, the area of the fire source, converted to the full scale, corresponds to 3.36 m×3.78 m, producing fires of 6.8–42.8 MW.

The longitudinal ventilation air flow in the tunnel model was created by a fan attached to the entrance of the model tunnel, as shown in Fig. 1. The flow velocity depends on the rotational speed of the fan, which is controlled by a frequency modulator. A hot-ball anemometer was mounted 8 m upstream of the fire to measure the air velocity, as shown in Fig. 1. The accuracy of the velocity measurement

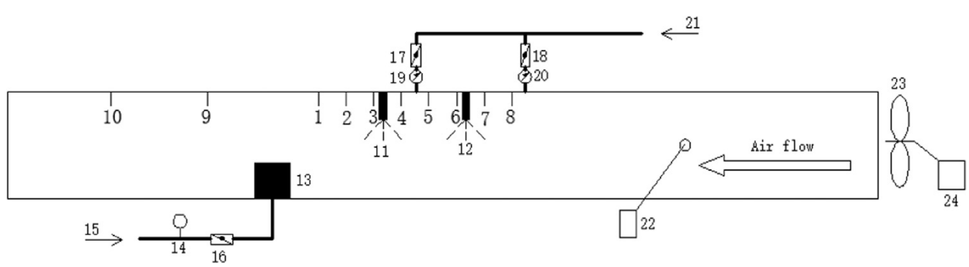

Fig. 1. Schematic diagram of the model tunnel. 1–10—Thermocouples ; 11—1# nozzle ; 12—2# nozzle ; 13—Burner ; 14—Rotameter ; 15—Propane gas ; 16–18—Control valve ; 19–20—Water pressure meter ; 21—Water pump ; 22—Anemometer ; 23—Fan ; 24—Frequency modulator.