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Effect of blockage ratio on critical velocity in tunnel model fire tests

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ABSTRACT

Experiments are conducted in a model tunnel of (1:20 of a tunnel section) to study the effect of blockage ratio on critical velocity. The vehicle blockage of the model tunnel is varied at 11 different blockage ratios, 9.4%, 15.6%, 21.9%, 25.0%, 31.3%, 34.4%, 40.7%, 43.8%, 50.1%, 56.3%, 59.5%. At the same time, the influence of heat loss in the experimental model on critical velocity is considered. The test results show that the critical velocity decreases with the increase of the blockage ratio, and the reduction ratio is less than the blockage ratio. The blockage-ratio modified coefficient obtained by experiment result is 0.545, and thus the formula of the critical velocity containing blockage ratio is proposed. The test results showed excellent agreement with from the formula of the critical velocity. The relationship between the critical velocity reduction ratio and the blockage ratio of this test and Oka and Atkinson (1995), Lee and Tsai (2012) and Kang (2010) were compared and analyzed. It is found that the main factors which lead to the different relationships about the critical velocity decrease rate and the blockage ratio are brought up, which include the height of fire burning surface, the location of fire source (the relative position about the fire source and blockage vehicles and whether the fire source is inside or outside the vehicle) and the lateral wall open area of vehicle.

1. Introduction

Fires have become a significant threat to the safety of tunnel transportation due to its catastrophic consequence (Hu et al., 2013; Meng et al., 2014). How to control smoke flow and efficiently exhaust smoke are of the critical factor for reducing catastrophic consequence, the key of the fire smoke control lies in the determination of critical velocity. The critical velocity is defined as the minimum longitudinal ventilation velocity to prevent reverse flow of smoke from a fire in the tunnel.

Currently, scholars have done a great deal of research on the critical velocity. Oka and Atkinson (1995) proposed a calculation formula of the dimensionless critical velocity based on the dimensionless heat release rate. Wu and Bakar (2000) used the tunnel hydraulic height as the feature length, proposed a calculation formula of the modified dimensionless critical velocity. Hu et al. (2008) studed the effect of near-wall fire on critical velocity. Zhong et al. (2013) revealed the Stack effect on critical velocity. Liu and Cassady (2014) studied the effect of point extraction on the critical velocity, and obtained the improved critical velocity model under specific conditions. Yi et al. (2014) and Weng et al. (2016) revised the critical velocity calculation based on the tunnel slope. Li and Ingason (2017) and Liu et al. (2017) proposed a critical velocity characterized by cross-section of the tunnel. However, most studies investigated critical velocity in tunnels without vehicles and did not consider the blockage effect of fire upstream vehicles on fire behavior and smoke. Obviously, this situation does not conform to the actual situation of vehicle congestion in tunnel fire, because the blocked vehicles will occupy part of the tunnel space, making the tunnel ventilation flow area decreases, thereby affecting the critical velocity.

The mode of Wuhan San-yang subway tunnel is adopted in this paper to carry out fire model tests under different blockage ratios. The effect of blockage ratio on critical velocity is discussed in detail. The relationship between the critical velocity reduction ratio k and the blockage ratio β of this test and previous studies (Oka and Atkinson, 1995; Kang, 2010; Lee and Tsai, 2012) are compared and analyzed.

2. Calculation and analysis of critical velocity with blockage

When there is no blockage in the tunnel, it is the tunnel cross-sectional area air supply, and the airflow is evenly distributed on the whole tunnel, the intensity of the ventilation flow does not change with the travel distance; When there is only blockage in the tunnel, the sectional area of the ventilation overcurrent becomes smaller. If the air supply per unit time remains unchanged at the hole, it will have a larger

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Nomenclature

A_{total}	tunnel cross-sectional area, m^2
$A_{obstacle}$	cross-sectional area of blockage, m^2
A_{local}	local sectional area, m^2
v_{total}	tunnel cross-sectional area ventilation velocity, m/s
v_{local}	local section ventilation velocity, m/s
v_{cr}	critical velocity, m/s
$v_{cr\text{-}ob}$	critical velocity with blockage, m/s
v_{cr}'	dimensionless critical velocity
Q	heat release rate, kW
$\bar{H}$	thydraulic diameter of tunnel, m
g	gravitational acceleration, m^2/s
c_p	thermal capacity of air, kJ/(kg·K)
T	smoke temperature, K
k_g	slope correction coefficient
Fr_c	critical Froude number, $Fr_c = 4.5$
k	reduced percentage, %

Greek letters

ρ_0	ambient air density, kg/m^3
β	blockage ratio, %

Subscripts

m	model scale
f	full scale

velocity when the ventilation air reaches the fire source, thus it has great thrust on the smoke, resulting in only a air supply velocity can counteract the upstream buoyancy-driven reversal flowing of smoke.

Tunnel blockage ratio β is defined as the ratio of cross-sectional area of blockage $A_{obstacle}$ to tunnel cross-sectional area A_{total}. When there is blockage in tunnel, the ventilation flow area of tunnel changes from cross section A_{total} to local section A_{local}, according to conservation of mass of fluid mechanics and the definition of β, the following relations can be found:

$$A_{total}v_{total} = A_{local}v_{local} = A_{total}(1-\beta)v_{local} \tag{1}$$

where v_{total} is the full section ventilation velocity, m/s; v_{local} is the local section ventilation velocity, m/s.

Because only the blockage is added in the tunnel, the other conditions are unchanged, therefore, assuming that the change of the critical velocity is only affected by the blockage, the critical velocity with blockage is

$$v_{cr-ob} = (1-\beta)v_{cr} \tag{2}$$

where $v_{cr\text{-}ob}$ is the critical velocity with blockage, m/s; v_{cr} is the critical velocity, m/s.

k is defined as the reduced percentage that critical velocity with blockage relative to no blockage, then there is

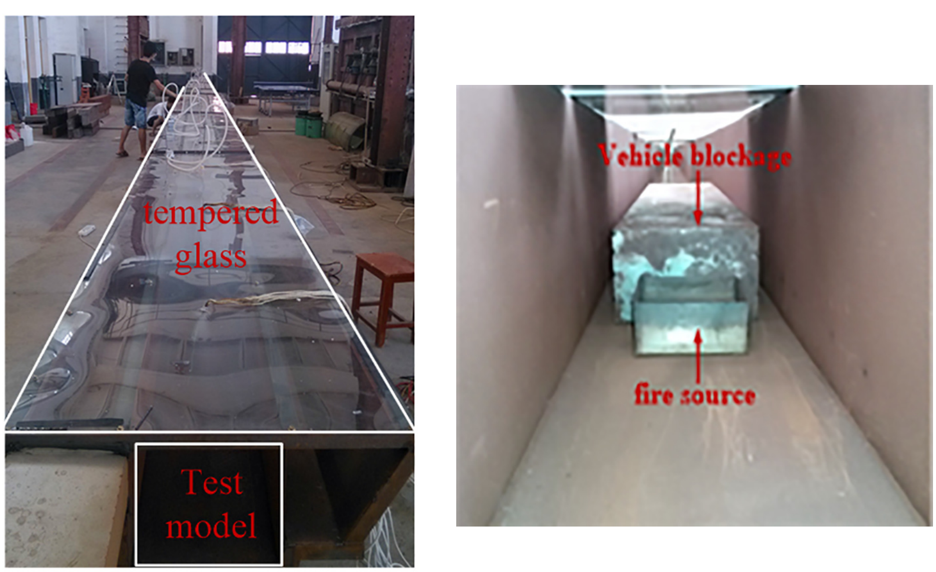
$$v_{cr-ob} = (1-k)v_{cr} \tag{3}$$

According to Eqs. (2) and (3), there should be $k = \beta$ in ideal state, but in fact $k \neq \beta$. For this reason, Oka and Atkinson (1995) and Li et al. (2010) found that k is slightly larger than β, when the β is 9%, 20%, 21% and 37% through model test. Li et al. (2012) studied the critical velocity when β is 0–70% using FDS, got that k is almost equal to β, and the degree of deviation was within 15%. Lee and Tsai (2012) carried out the test with 2 rows of small, medium, large 3 types of vehicles (β is 5%, 15% and 21%, respectively). When the fire source is located on the centerline of a row of car (fire source 1), the critical velocity increases by 0.0%, 8% and 10% respectively than the critical velocity without blockage. When the fire source is located on the tunnel center line between two rows of trains (fire source 2), the critical velocity increases by 2%, 14% and 16% respectively than the critical velocity without blockage. That is 2 different fire source locations obtained 2 opposite relationship between k and β. It can be seen that the relationship between k and β, in these research results is not the same. Therefore, this paper will make a comparative analysis of the causes based on the results of model tests.

3. Experiment

3.1. Test device

The test model is built on the basis of Froude similarity criterion



(a) Test model (b) Test site

Fig. 1. Model test device.