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Investigation on the critical shaft height of plug-holing in the natural ventilated tunnel fire

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ABSTRACT

In order to study the plug-holing of vertical shaft with different fire-shaft distance in road tunnel, a series of numerical simulations about tunnel fire were carried out. The results have shown that the smoke layer thickness under the ceiling increases with the increase of smoke spreading distance and it is mainly affected by tunnel width when the fire heat release rate is in the range of 3–15 MW. In the wider tunnel, the dimensionless smoke temperature rise decays faster in exponential. While the smoke velocity shows a well correlation with the smoke layer thickness and dimensionless temperature rise beneath the ceiling. Both the wider tunnel and larger area of shaft vent contribute to the occurrence of plug-holing. The fire heat release rates have little effect on the critical shaft height of plug-holing, which is mainly controlled by smoke layer thickness, area of shaft vent, tunnel width as well as the side length of shaft vent. On the whole, the influence of aspect ratio of shaft vent on the critical shaft height of plug-holing is complex. Based on the theoretical analysis and simulation results, a new prediction model considering the factor of fire-shaft distance is deduced to predict the critical shaft height in the tunnel with natural exhaustion through vertical shaft.

1. Introduction

Nowadays, more and more road tunnels are constructed to relieve traffic congestion in China. However, tunnel fire is still a great threat because of the toxic smoke gas spreading along the tunnel ceiling, which prohibits the safe evacuation of occupants and makes it difficult for firefighters to extinguish fire [1,2]. Therefore, it is crucial to control the smoke movement and exhaust them promptly in tunnel fire.

There are mainly two kinds of ventilation system in road tunnels, i.e. the natural ventilation and the mechanical ventilation [3,4]. Compared with the mechanical ventilation, the natural ventilation with vertical shaft is economical, does not need extra power and special equipment, which has been used in more and more urban road tunnels [5]. Currently, many scholars have conducted extensive research on smoke control of fire in road tunnel with vertical shaft.

Wang have conducted some full-scale experiments on fire in tunnels with roof openings, to study the effect of natural ventilation as well as the smoke backflow distance [6]. Yoon has found that the natural ventilation pressure induced by the shaft has a significant impact on the efficiency of the ventilation system [7]. Ji also analyzes the influence of cross-sectional area and aspect ratio of shaft on natural ventilation in urban road tunnel fires by Large Eddy Simulation, and it comes to conclusion that the shaft with larger cross-sectional aspect ratio should be divided into several smaller shafts in order to exhaust as much smoke as possible [8]. Huang investigated numerically the effect of ventilation shaft arrangement and shaft geometry on natural ventilation performance in a subway tunnel by Fluent [9].

As a matter of fact, the smoke exhausting process by vertical shaft is mainly controlled by the horizontal inertia force of smoke and the vertical inertia force induced by stack effect [10]. When the vertical inertia force induced by stack effect of tunnel shaft is large enough, the fresh air will be drawn directly into the shaft vent from the lower layer, which means the plug-holing phenomenon occurs, resulting in the smoke exhaust efficiency decreasing significantly [11,12].

Fan and Ji have made some perspective studies on the plug-holing phenomenon by both model tunnel experiments and numerical simulations. They investigated the evolutionary process of plug-holing phenomenon and studied the influence of geometry as well as height of shaft on the plug-holing. In the tunnel fire with vertical shaft, the ratio of the vertical inertia force induced by stack effect to the smoke's horizontal inertia force was proposed as the new criterion to determine whether the plug-holing phenomenon occurs. The lowest shaft height

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Nomenclature

a	side length of shaft vent (m)
c_p	thermal capacity of air ($J \cdot kg^{-1} \cdot K^{-1}$)
d_s	thickness of smoke layer under the ceiling (K)
F_V	vertical buoyancy force caused by shaft (N)
F_H	horizontal buoyancy force of smoke (N)
g	gravitational acceleration (m/s^2)
h	height of vertical shaft (m)
h_c	critical height of vertical shaft (m)
Q	total heat release rate (kW)
Ri	a dimensionless number (-)
x	distance between measuring location to reference location (m)
x_{ref}	distance between reference location to fire source (m)
A	cross-sectional area of shaft vent (m^2)
D^*	the characteristic length scale
T_0	ambient air temperature (K)
T_s	temperature of smoke gas (K)
V_s	velocity of smoke gas (m/s)
H	Tunnel height (m)
W	width of tunnel (m)
D^*	ambient air density (kg/m^3)
ρ_s	smoke density (kg/m^3)
λ	scale factor (-)

when the plug-holing occurred was defined as critical shaft height. However, most of Ji's investigations were based on the situations where the distance between fire source and vertical shaft was constant and they did not consider the influence of different fire-shaft distance on the plug-holing.

It is known that both the vertical inertia force induced by stack effect and the smoke's horizontal inertia force have a close relationship with the smoke temperature, while the smoke temperature decays with the increase of smoke spreading distance under the tunnel ceiling. Therefore, the critical shaft height of plug-holing might change with the different distance between fire source and vertical shaft. Nowadays, few papers have studied the influence of fire-shaft distance on the critical shaft height, and the mechanism between them has never been revealed before. On the other hand, the plug-holing could decrease the smoke exhaust efficiency, it is essential to study the critical shaft height under different fire-shaft distance to prevent the occurrence of plug-holing in the tunnel fire. Meanwhile, it also provides useful references for the distance between vertical shafts in tunnel ventilation design.

In current paper, a series of numerical simulations were conducted to study the plug-holing phenomenon with different distances between fire source and vertical shaft. The characteristics of smoke layer thickness, smoke velocity and dimensionless smoke temperature distribution are investigated. The controlling factors of the plug-holing are determined and a dimensionless model to predict the critical shaft height of plug-holing was proposed based on the theoretical analysis and simulation results.

2. Theoretical analysis

The primary function of smoke exhausting by vertical shaft in tunnel fire is stack effect, which is induced by the temperature difference between ambient fresh air and hot smoke gas in shaft. The temperature difference is the density difference in essence, which leads to the buoyancy force driving the smoke move vertically in shaft. The stack effect can be expressed by

$$\Delta P = (\rho_0 - \rho_s) g h \tag{1}$$

Assuming the smoke temperature in shaft is uniform [13] and substituting the ideal gas equation into Eq. (1), it will be,

$$\Delta P = \rho_0 T_0 \left(\frac{1}{T_0} - \frac{1}{T_S} \right) g h \tag{2}$$

Except the vertical buoyancy force caused by the stack effect, the horizontal inertia force of smoke also has a great influence on the smoke exhausting process by vertical shaft. The viscous force could be ignored because the friction factor of shaft is very small compared with the inertial force [13]. According to the competition relationship between them, Ji has proposed a dimensionless number Ri, which is the ratio of the vertical buoyancy force caused by the stack effect to the horizontal inertia force generated by fire source [13], as the criterion to determine the occurrence of plug-holing. Based on the dimensionless number Ri, the critical shaft height could be obtained as following.

The vertical buoyancy force caused by the stack effect is

$$F_V = \Delta P \cdot A = \rho_0 T_0 \left(\frac{1}{T_0} - \frac{1}{T_S} \right) g h A \tag{3}$$

The horizontal buoyancy force generated by fire source is

$$F_H = \rho_S V_S^2 d_S W \tag{4}$$

According to the ideal gas equation, it is $\rho_0 T_0 = \rho_S T_S$, then $\rho_S = \rho_0 T_0 / T_S$.

Considering $\Delta T_S = T_S - T_0$, the dimensionless number Ri will be

$$Ri = \frac{F_V}{F_H} = \frac{\rho_0 T_0 \left(\frac{1}{T_0} - \frac{1}{T_S} \right) g h A}{\rho_S V_S^2 d_S W} = \frac{T_S \left(\frac{1}{T_0} - \frac{1}{T_S} \right) g h A}{V_S^2 d_S W} = \frac{\Delta T_S g h A}{T_0 V_S^2 d_S W} \tag{5}$$

When the plug-holing phenomenon has just occurred from nothing, the corresponding dimensionless number Ri is the critical number, Ri_C, then the vertical shaft height is defined as the critical height, h_C, and it is as following,

$$h_C = \frac{T_0 V_S^2 d_S W}{\Delta T_S g A} \times Ri_C \tag{6}$$

When the density difference between the smoke flow current and the ambient airflow is small, Bailey proposed a velocity prediction model for the smoke under the corridor ceiling as following [14],

$$V_S \propto \sqrt{g d_S \frac{\Delta T_S}{T_0}} \tag{7}$$

Submitting the smoke velocity equation (7) into the above equation (6), the dimensionless smoke temperature rise ($\frac{\Delta T_S}{T_0}$) is eliminated, and the critical shaft height becomes,

$$h_C \propto \frac{d_S^2 W Ri_C}{A} \tag{8}$$

From the results of theoretical analysis, it can be known that the critical shaft height of plug-holing is mainly controlled by the vent area of vertical shaft, A, the tunnel width, W, the critical dimensionless number Ri_C as well as the square of smoke layer thickness d_S under the tunnel ceiling. According to Ji's research result [13], the critical dimensionless number Ri_C is 1.4.

3. Numerical simulation

Fire Dynamic Simulator (FDS) [15], developed by U.S. National Institute of Standards and Technology, is a popular computational fluid dynamic software package in fire safety area that mainly solves the Navier-Stokes equations based on finite volume method. It is often used to study the tunnel fires and achieves a great success [16–18]. In this paper, the large eddy simulation (LES) method is used, coupled with