Applied Thermal Engineering 109 (2016) 344–350

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Simulation of back-layering length in tunnel fire with vertical shafts

Yan Fu Wang [*], Xiao Fei Sun, Shuai Liu, Pei Na Yan, Tao Qin, Biao Zhang

Department of Safety Science and Engineering, China University of Petroleum, Qingdao, China

HIGHLIGHTS

- Back-layering length is researched theoretically and experimentally.
- Effects of shaft dimension, amount and the distance on back-layering length are researched.
- Prediction formula for calculating back-layering length is proposed based on fire plume theory.

ARTICLE INFO

Article history:
Received 25 May 2016
Revised 12 August 2016
Accepted 13 August 2016
Available online 16 August 2016

Keywords:
Back-layering length
Tunnel with vertical shafts
Theoretical analysis
Computational fluid dynamics

ABSTRACT

It is known that costs to install and operate tunnels with vertical shafts are lower than the conventional tunnel. However, currently, there is no universally accepted theory to calculate and assess the smoke exhausting efficiency when there is a fire in this new type of tunnel. In this paper, theoretical analysis is carried out to predict the back-layering length of fire in the tunnel with vertical shafts. Firstly, a theoretical model is proposed based on fire plume theory. Secondly, Computational Fluid Dynamics (CFD) is used to research the effect of shaft geometry on back-layering length. Thirdly, the calculation results from the proposed model are compared with both experimental data and simulation results. The comparison results show that the proposed theoretical model can be used to predict the back-layering length of fires in tunnel with vertical shafts.

1. Introduction

Fires in tunnels have been attracting increasing attention in recent years due to its catastrophic consequence [1–4]. Due to the special structure, the hot gases will spread to a long distance along the tunnel ceiling driven by the buoyancy force as well as by the longitudinal forced air flow [5]. As the length of tunnel increases, it becomes difficult not only to eliminate contaminants in tunnel but also to control emergency situations, especially fires. This causes an enormous increase in the expense of the ventilation system. Instead of using fan, tunnels with vertical shafts ventilate naturally. Apart from cost saving, natural ventilation not only could exhaust high temperature smoke, but also facilitates airflow exchange to improve interior air quality [6].

With the popularity of tunnels with multiple vertical shafts, increasing amount of efforts has been directed into researching the natural ventilation in the tunnel with vertical shafts [7]. A series of full-scale fire experiments of tunnel with vertical shafts are conducted [8,9] from which a prediction equation is proposed for calculating back-layering length [10]. A theoretical model is also built to predict the back-layering length considering the effect of the distance between ceiling extraction and fire source [11,12]. An equation is proposed to express the relationship between the dimensionless back-layering length and the temperature decay [13] through reduced-scale fire experiments [14]. Experiments are also conducted to research the influencing factor of back-layering length: such as, the effect of a vehicular blockage [15,16] and longitudinal ventilation with a vertical shaft [17] on the back-layering length of tunnel fires.

Some other references adopt CFD model to research the back-layering length. Large Eddy Simulations are applied to predict the effect of the vent size and fire source location [18] and longitudinal wind [19] on the back-layering length in tunnel with vertical shaft. The pressure losses through shafts are optimized through CFD modeling [20]. The temperature and the time taken by the hot gases through vertical shaft are analytically and numerically estimated [21].

All above studies research the back-layering length in tunnel fire. However, theoretical analyses on how shaft dimension and arrangement influence back-layering length have rarely been addressed. To fill in the gap, the effects of shaft quantity and dimension on back-layering length are theoretically researched in this paper.

---

[*] Corresponding author.
E-mail address: wangyanfu@upc.edu.cn (Y.F. Wang).

http://dx.doi.org/10.1016/j.applthermaleng.2016.08.081
1359-4311/

Nomenclature

H_d	height from fire source to ceiling, m
Q	heat release rate, kW
ρ_0	density of air, kg/m^3
T_0	ambient temperature, K
c_p	specific heat at constant pressure, kJ/(kg K)
m_s	exhausting rate of pure smoke, kg/s
m_t	smoke exhausting rate through shaft, kg/s
co_{shaft}	carbon monoxide concentration of the smoke inside vertical shafts, ppm
ρ_s	the smoke density, kg/m^3
$\Delta T_{\max,d}$	the maximum temperature rise at a certain transverse location beneath ceiling, K
h	the height of vertical shafts, m
$\dot{Q}_c$	convection part of heat release rate, kW
ΔT_x	the maximum temperature rise at x m location away from fire source, K
ΔP_{st}	the static pressure difference, Pa
h'	the thickness of smoke back-layering front, m
z	the height away from fire source surface, m
u	smoke flow velocity, m/s
$\dot{Q}'$	the actual heat in tunnel, kW
D	the distance from fire source to side wall, m
W	the width of tunnel, m
d	the distance away from fire, m
n	the number of vertical shafts of one group
w	the width of vertical shaft, m
l	the length of vertical shaft, m
co_{tunnel}	carbon monoxide concentration of the smoke under tunnel ceiling, ppm
v_s	exhaust velocity, m/s
$\Delta\rho$	the density difference between ambient air and smoke, kg/m^3
ΔT	the temperature difference between ambient air and smoke, K
U	cross sectional perimeter of tunnel, m
k	convective heat transfer coefficient of tunnel J/(K m^2 s)
P_{dy}	the dynamic pressure, Pa
$\dot{m}$	mass flow rate of smoke under tunnel ceiling, kg/s
G	hydraulic diameter of tunnel, m
v	the longitudinal air flow velocity, m/s

2. Theories

2.1. Back-layering

In tunnel fires, the ceiling jet is formed when the fire plume collides with the ceiling. Smoke front spread being driven by the horizontal inertia force, which is caused by the temperature difference between the hot smoke and ambient air. The temperature difference becomes smaller and smaller when smoke exchanges heat with ambient air during diffusion. So the horizontal inertia force is also decreased. When it equals to the resistance from longitudinal wind, the smoke front will remain stagnant and this diffusion distance is called back-layering length. The back-layering phenomenon, which is shown in Fig. 1, is one of the important subjects worth studying because it results in the firefighter being exposed to radiation from the hot smoke.

2.2. Plug-holing

Stack effect is the primary driving force of exhaust under natural ventilation conditions. The disturbance on smoke layer interface beneath the vent is strengthened with the stack effect enhancing. When the shaft reaches a certain height, the smoke layer thickness beneath vent decreases to 0 which means the fresh air is drawn directly into the shaft from the air layer inside the tunnel. This special phenomenon is called as plug-holing [7,22] as shown in Fig. 1. The carbon monoxide concentration both inside the vertical shaft and in the smoke layer beneath ceiling can reflect the air entrainment degree [23]:

$$\frac{co_{shaft}}{co_{tunnel}} = \frac{\dot{m}_s}{\dot{m}_t} \tag{1}$$

2.3. New model of back-layering length

The maximum smoke temperature rise at x m away from fire source can be expressed as [24,25]:

$$\frac{\Delta T_x}{\Delta T_{\max}} = \exp\left(-\frac{kU}{c_p\dot{m}}\cdot x\right) \tag{2}$$

where k is the heat convection parameter, J/(K m^2 s); k can be expressed as [26]:

$$k = 2.33k'u^{1/2} \tag{3}$$

where k' = 7.5 (k' can be chosen from 5 to 10); u = 0.9 m/s according to the full scale experiment [9], so k is 16.58 J/(K m^2 s).

When back-layering occurs, the smoke front will interact with the longitudinal air flow. The buoyancy or the static pressure difference between the smoke front and the ambient air drives the smoke front spreading. At the position where the static

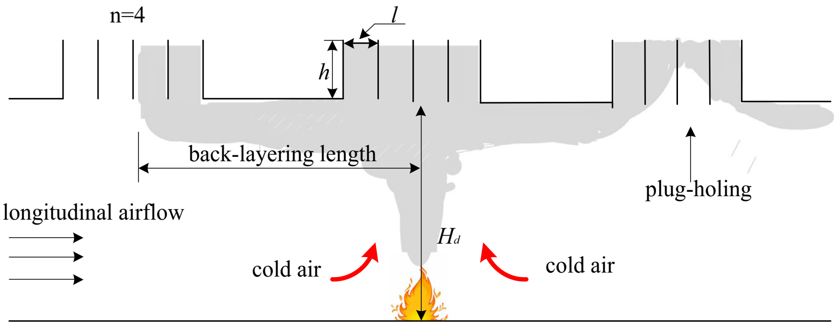

Fig. 1. Phenomena of back-layering and plug-holing.