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A comprehensive study of two fire sources in a road tunnel: Considering different arrangement of obstacles

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ABSTRACT

This paper uses Fire Dynamics Simulator (FDS) to study various arrangements of different vehicles at upstream of two fire sources. In order to make a comprehensive study, the effects of two fire sources in both lateral and longitudinal directions are investigated. The results reveal that the behavior of two fire sources, in both perpendicular directions, is directly influenced by distance between them. For small vehicles, variations of the arrangement and distance between the vehicles and fire sources do not affect the calculated Critical Ventilation Velocity (CVV). However, the presence of medium vehicles strengthens the influence of inertia force rather than buoyant force of fire plume in the tunnel. Accordingly, when there is a short distance between fires and medium obstructions, less air ventilation is needed to prevent smoke back-layering. Eventually, far distance between the vehicles and the fires results in vanishing obstruction effects. Consequently, CVV is the same as the case in which there is no vehicle in the tunnel.

1. Introduction

Generally, fire in a road tunnel forms a complicated structure. This physical phenomenon which involves chemical reaction, turbulence, and radiation is affected by various parameters, including geometry, tunnel slope, ventilation velocity, sidewalls restriction, and pressure of passing air among other influential variables. Once a fire occurs in a road tunnel; inhaling the distributed smoke throughout the tunnel is more dangerous issue than direct contact of individuals to the fire (Hu et al., 2005). Therefore, optimized control of smoke distribution is one of the crucial studies in design of ventilation systems, and it is indispensable to comprehend the characteristics of smoke distribution in order to reach successful design. When a fire occurs in the tunnel, the longitudinal ventilation system turns on in order to prevent back-layering flow of smoke and provide a safe region for people to escape. The low ventilation velocity allows combustion products to have counter-flow movement. The magnitude of Critical Ventilation Velocity (CVV) and fire Heat Release Rate (HRR) are two substantial initial conditions required for designing longitudinal ventilation system in tunnels.

Thomas (1968) depicted an analytical relation between original ventilation velocity and back-layering flow based on a comparison between buoyant force of the fire plume and inertia force of ventilation velocity. This method was studied by numerous investigators. Oka and Atkinson (1995) studied smoke movement in a real tunnel which was modeled by 1:10 scale and observed that critical velocity behavior in the modeled tunnel is similar to real one. They investigated the effect of various parameters such as tunnel shape, size, and obstruction on CVV. They found that when 12% of cross section of tunnel is occupied with the obstruction, the ratio of $(V_{Cr,\ Unoccupied}\text{-}V_{Cr,\ Occupied})/V_{Cr,\ Unoccupied}$ is about 15% and when 40–45% of tunnel is occupied this ratio would increase to 32%. Wu and Bakar (2000) studied the effect of cross section geometry of a small scale tunnel on CVV. They proposed that in order to apply the effect of geometry of the cross section, it is appropriate to use hydraulic height of tunnel in CVV relation.

Modic (2003) considered the effect of tunnel slope in the relation which was presented by Thomas (1968). Also, experimental studies were carried out in a 1:10 reduced-scale modeled tunnel to study the influence of slope on CVV (Yi et al., 2014). In this study the experimental results agreed well with previous studies. Hwang and Edwards (2005) investigated ventilation velocity in the fire plume and jet region, close to the ceiling, and concluded that CVV has a direct proportion to $Q^{1/5}$ (Q is HRR) and this achievement was based on Quintiere (1989) analysis. Quintiere studied fluid flow in the tunnel and stated that cross section geometry of tunnel has influence on CVV. When this geometry changes, the fire dynamic would change as well.

Gao et al. (2014) investigated the influence of sidewall restriction on the maximum ceiling gas temperature in a

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Nomenclature

C_p	constant pressure specific heat ($m^2\,s^{-1}$)
d	distance between two fires (m)
D	diffusion coefficient
g	acceleration of gravity ($m\,s^{-2}$)
h_s	sensitive enthalpy ($kJ\,m^{-3}$)
L	distance between vehicles and fire
$\dot{m}_b'''$	mass production rate of species by evaporating droplets/particles ($kg\,m^{-3}\,s^{-1}$)
p	pressure ($kg\,m^{-1}\,s^{-2}$)
$\dot{q}$	heat release rate (kW)
$\dot{q}'''$	heat release rate per unit volume ($kW\,m^{-3}$)
$\dot{q}''$	heat flux vector ($kW\,m^{-2}$)
$\dot{q}_r''$	radiative flux to a solid surface ($kW\,m^{-2}$)
R	universal gas constant ($J\,K^{-1}\,mol^{-1}$)
t	time (s)
T	temperature (k)
$\boldsymbol{u}$	velocity vector ($m\,s^{-1}$)
V_{Cr}	critical ventilation velocity ($m\,s^{-1}$)
W_α	molecular weight of gas species ($kg\,mol^{-1}$)
X	longitudinal direction of tunnel (m)
Y_α	mass fraction of species α
Z	heightened-direction of tunnel (m)

Greek symbols

ρ_0	initial air density ($kg\,m^{-3}$)
τ_{ij}	viscous stress tensor ($kg\,m^{-1}\,s^{-2}$)
ε	dissipation rate ($kg\,m^{-1}\,s^{-3}$)
$\mathcal{H}$	total pressure divided by density ($m^2\,s^{-2}$)
$\check{p}$	pressure perturbation ($kg\,m^{-1}\,s^{-2}$)
ω	vorticity vector (s^{-1})

buoyancy-driven thermal flow experimentally. They concluded that decreasing the distance of fire source to the walls does not have significant effect on the maximum temperature when fire is far from the walls, but next to the wall the maximum temperature soars drastically. Finally, they proposed a new correlation for the maximum ceiling gas temperature. Ji et al. (2012) set an experimental model to study the effect of various transverse fire locations on maximum smoke temperature under the tunnel ceiling. They also stated that due to the restriction effect of the sidewalls of tunnel the maximum smoke temperature goes up compared with unconfined space. Gao et al. (2015) implemented 48 experiments with four experimental setups to study the details of flame shape and flame length under the ceiling of a channel and concluded that the flame shape is a function of HRR and flame position.

Li et al. (2010) investigated the effect of the presence of the accident vehicles obstructions on CVV and length of back-layering in which the obstacles occupied 20% of cross section of the tunnel. They presented that due to presence of the vehicles, CVV reduced about 23%. Tsai et al. (2010) evaluated the value of CVV with two heat sources in a tunnel numerically and experimentally. They depicted that CVV descends when the distance between two sources is far significantly and in this case, the ventilation velocity must be calculated only by considering the more powerful source. Since smoke flow of the more powerful source has dominant power with respect to less powerful one, the back-layering effect of small source becomes comparatively negligible. Lee and Tsai (2012) studied the effect of vehicles obstruction on CVV and length of back-layering experimentally. They applied Different arrangement of vehicles in which 3–31% of the cross section was occupied and stated that in the case that longitudinal ventilation flow is in the direct access to fire, CVV reduces. Whereas, in the case that vehicles arrangement is placed in the way which prevents direct ventilation flow to the heat source, it leads to soar HRR and consequently increase of CVV. The influence of an obstacle blockage according to its location compared with the tunnel floor on the back-layering flow behavior and the critical velocity is performed numerically by using FDS (Gannouni and Maad, 2015). This study depicted that the effect of obstacle blockage brings about a decrease of CVV compared to those obtained with an empty tunnel. Previous studies show that the two passes road tunnels which were plugged by traffic jam and car accident causes fire adventure (Ingason, 2008). Mapar et al. (2013) investigated the effect of fire longitudinal location on CVV. They observed that increase of distance between fire and entrance of the tunnel leads to decrease in CVV.

Based on the earlier investigations, the state which two fire sources in the presence of multi vehicles phenomenon has not been evaluated. Nevertheless, the history of car accident in the tunnel such as Mont Blanc (Henke and Gagliardi, 2004) and Gotthard (Vuilleumier et al., 2002) suggests that usually the number of fire has been more than one and other vehicles are in the tunnel during accident. Therefore, in the present study to increase human safety level that passes through the tunnel, CVV with Different arrangement of vehicles and diverse sizes in the upstream of two fire sources is investigated. In order to simulate this phenomenon, this study uses Fire Dynamics Simulator (FDS) code, version 6. Experimental results from Lee and Tsai (2012) allow this study to validate the numerical simulation results with experimental measurements. Moreover, the effects of distance between obstruction from the fire and also the distance between two fire sources on the critical ventilation velocity have been evaluated.

2. Physics of tunnel fire

There are several stages in developing a fire scenario including ignition, spread, flashover, fully developed fire, and decay. Since the heat release rate of a fully developed fire is in its maximum value, the most challenging state for firefighters to control situation is when fire is fully developed (Pasdarshahri et al., 2013). In the present study, this scenario, i.e. the fully developed fire in a tunnel is studied. A schematic of fire flow is shown in Fig. 1. When a fire occurs in a tunnel due to buoyant force, the combustion products move up and reach to the tunnel ceiling. These hot gases initiate to distribute along the longitudinal sides of the tunnel and consequently great volume of smoke and heat disperse throughout the tunnel. The presence of smoke particles provides a region which not only has got insufficient oxygen but also reduces the magnitude of individual's sight for escaping. One of the best scenarios for escaping people in such venturesome situations is the time which longitudinal ventilation system is considered in tunnel. In other words, longitudinal ventilation causes an air flow in this direction. In this case, fresh air blows to the fire from one side of tunnel and therefore it prevents distribution of soot and combustion products to the upstream part of the fire. In addition, using longitudinal ventilation causes temperature and concentration of smoke to decline and prevents back-layering phenomenon; consequently, it enables the individuals to move away more convenient. CVV is a minimum ventilation velocity which ceases smoke back-layering phenomenon. Moreover, the back-layering length, showed in Fig. 1, becomes zero on account of this ventilation velocity.