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Effects of buoyancy induced roof ventilation systems for smoke removal in tunnel fires

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ABSTRACT

The present article highlights the performance of natural roof ventilation systems and its effects on tunnel fire flow characteristics. Numerical analysis is performed using Large Eddy Simulations (LES) to predict fire growth rate and smoke movement in tunnel with single and multiple roof openings. The smoke venting performance of ceiling vents are investigated by varying the vent size and fire source locations. The critical parameters such as mass flow rate through ceiling openings, smoke traveling time and fire growth patterns are presented. The ceiling openings are effective in transferring hot gases and reduces the longitudinal smoke velocity. The heat source and ceiling vent locations significantly affects the vent performance and smoke behavior in tunnel. The present results are in good agreement with the experimental results available in literature.

1. Introduction

The tunnel fire is the major hazard which endangers human life, environment and property. In the event of fire accidents, fire spreads quickly and passengers are exposed to smoke and toxic gases. The limitations in the number of fire escape routes and difficulty for emergency services to access fire accident location increases the risks and vulnerability of accidents. With increase in traffic densities and with construction of longer tunnels, the possibility of fire accidents increases. In the past several fire accidents were reported which includes Mont Blanc-Tunnel fire (Vuilleumier et al., 2002) between Italy and France in 1999, which killed 39 people and Daegu subway fire (Hong and Hwa, 2004) in Korea in 2003 which killed 198 people. To ensure safety measures in tunnel, ventilation systems are designed for supplying clean ambient air and to reduce the soot and toxic gases which endanger human life during emergency conditions. Tunnel ventilation systems are generally classified into mechanical and natural ventilation systems. Most of the tunnels are equipped with longitudinal mechanical ventilation systems that require installation of fans to induce airflows and ducts to distribute the airflow.

Oka and Atkinson (1995) experimentally studied the effect of forced longitudinal velocity in controlling tunnel upstream smoke movement by varying the size and location of fire source. Based on their experimental findings empirical correlations were established to relate the influence of critical velocity on heat release rates. Numerical simulations (Chow, 1998; Wu and Bakar, 2000; Li and Chow, 2003) were performed to predict fire transport phenomena and to evaluate the capability of different tunnel ventilation systems. Numerical investigation by Large Eddy Simulations (LES) were carried out in ventilated tunnel (Lee and Ryou, 2005) with different aspect ratios to predict the smoke movement and temperature distribution. Experimental studies (Hu et al., 2007) were conducted in road tunnel with different longitudinal velocities and ceiling jet temperature distribution upstream and downstream of the fire source were analyzed. The temperature distributions in mechanical ventilated tunnels (Li et al., 2012) were analyzed and the proposed correlation was validated with experimental results. Experimental investigations (Hyun Ko et al., 2010) were carried out in ventilated tunnel with fire source to study the effect of tunnel slope. The angle of tunnel slope was varied and inclination effects were analyzed with different fire size and ventilation velocities. Small scale (Tsai et al., 2010) experimental and numerical simulations were performed in tunnel with two fire sources under forced ventilation conditions. All the above studies focused on critical ventilation velocities in tunnel to prevent back layering of smoke under forced ventilation conditions.

Full-scale experiments (Wang et al., 2009a,b) were conducted to study the smoke removal efficiency in naturally ventilated tunnels with roof openings. The above study highlighted that most smoke flow out of the tunnel through roof openings. Recent studies (Yuan-dong et al., 2011; Ji et al., 2012; Fan et al., 2013) were performed in naturally ventilated tunnels with vertical ventilation

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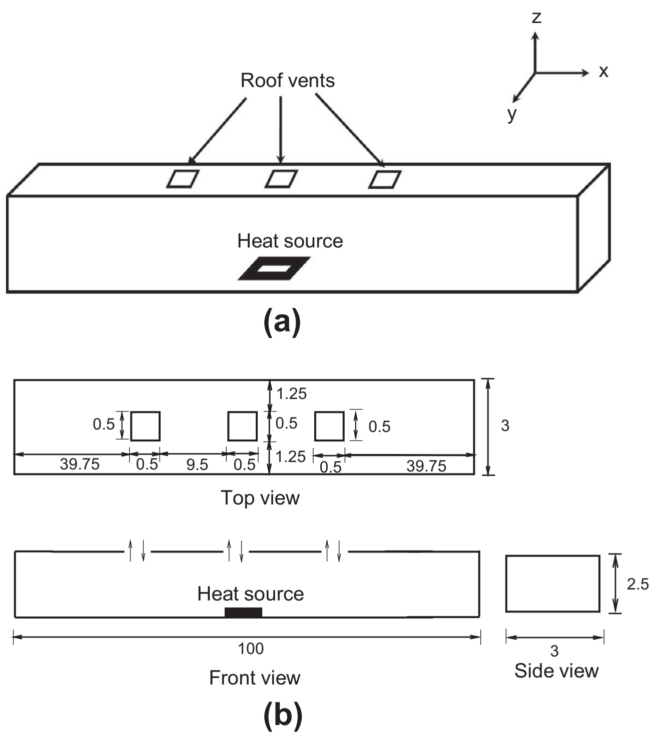

Fig. 1. Schematic diagram of tunnel with roof openings (a) 3-D view and (b) 2-D view (dimensions in m).

shafts. Their study concluded that ventilation shafts are more efficient as chimneys for smoke exhaust and increases natural ventilation pressure. Experimental investigations (Vauquelin and Megret, 2002) were performed in tunnel fires equipped with mechanical smoke extraction system. Recent studies (Chow and Gao, 2009; Chow and Li, 2011; Harish and Venkatasubbaiah, 2013a,b; Venkatasubbaiah and Jaluria, 2012) on fire induced air flow in partial enclosures investigated on smoke removal through ceiling vents.

Recent article (Zhong et al., 2013) on tunnel ventilation investigated on mixed mode ventilations, influence of forced longitudinal ventilation on natural roof ventilation. The effects of longitudinal wind on stack effect phenomena (Zhong et al., 2013) in ceiling mounted shafts were analyzed by Large Eddy Simulations. The

Table 1
Smoke layering length for heat release rate of 80 kW.

Point extraction velocity (m/s)	Upstream		Downstream	
	Present (m)	Experimental (Chen et al., 2013) (m)	Present (m)	Experimental (Chen et al., 2013) (m)
1.5	18.48	19	19	18.5
1.8	14.1	14.5	15	14.5

Table 2
Grid independence with three mesh sizes.

S. no	*x* Cells	*y* Cells	*z* Cells	Total number of cells
1	1200	36	32	1,382,400
2	1500	48	40	2,880,000
3	1620	50	40	3,240,000

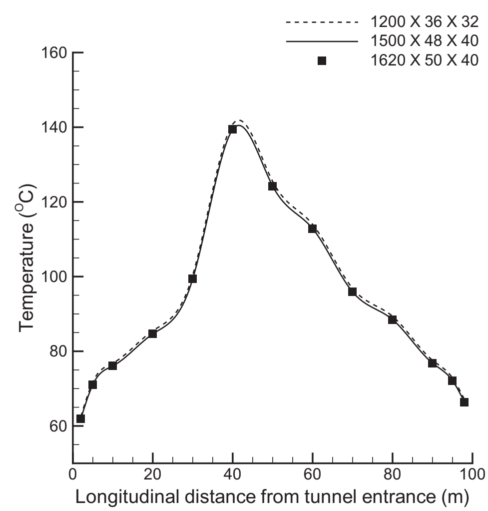

Fig. 3. Temperature variation towards the tunnel upstream side measured from fire source.

critical longitudinal velocity suitable for better smoke removal was identified. Experimental and numerical investigations (Ingason and Li, 2011; Chen et al., 2013) were carried out to

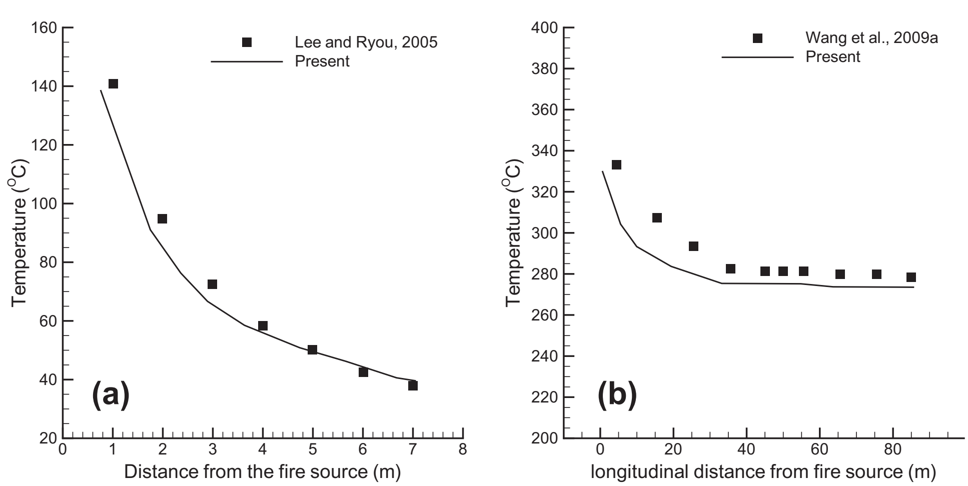

Fig. 2. Validation of present results with experimental results.