Tunnelling and Underground Space Technology 61 (2017) 189–197

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Multiple steady states of fire smoke transport in a multi-branch tunnel: Theoretical and numerical studies

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ARTICLE INFO

Article history:
Received 15 January 2016
Received in revised form 15 September 2016
Accepted 20 October 2016

Keywords:
Tunnel
Buoyancy
Multiplicity
Smoke transport
Ventilation

ABSTRACT

The multiplicity of smoke flow states may pose a great threat to both human evacuation and emergency rescue in tunnels. A case study is conducted to investigate the multiple steady states of fire smoke transport in a triple-branch tunnel. Both theoretical analysis and numerical simulation are employed in this study. For the case examined in this study, at least three flow regimes are identified under the effects of similar boundary conditions. The results indicate that even for a "well-designed" smoke exhaust system, multiple flow regimes could exist and some flow modes could threaten the human evacuation. The operating point of the mechanical fan system shifts due to the transition between multiple flow regimes. The preliminary results indicate that the inclination angle of the inclined tunnel branches could play an important role in the multiplicity of smoke flow states in such a tunnel system.

1. Introduction

The urban traffic tunnels, which are located underground central urban districts (Hua et al., 2011; Du et al., 2015), are effective for vehicle transportation in areas with high traffic density. To ease the ground traffic pressure, urban traffic tunnels are usually required to connect more than one ground road (as shown in Fig. 1). This requirement means that an urban traffic tunnel could become a multi-branch tunnel system with several portals, i.e., more than one link tunnel is built to connect the underground main tunnel and the ground traffic roads. Furthermore, these link tunnel branches are typically inclined tunnels because of the difference between the ground and underground levels. In the event of a fire accident, the structural complexity of a multi-branch urban traffic tunnel could cause difficulties for smoke control. Hot and toxic smoke could be the primary factor for casualties (Yang et al., 2011, 2012; Ji et al., 2012; Mao and Yang, 2016). Transverse or centralized smoke extraction is usually employed in tunnels (Yi et al., 2015; Fan et al., 2013a; Chen et al., 2013). For an ordinary tunnel, e.g., a horizontal single tunnel, the activation of a smoke exhaust system results in a unique smoke discharge route (Fan et al., 2013b; Tang et al., 2014). Thus, both the route for human evacuation and that for emergency rescuers can be determined in the emergency plan. The safety of these preset routes can therefore be guaranteed when a fire occurs. However, a fire occurred in a multi-branch urban traffic tunnel could have more than one route for smoke transport even if the smoke exhaust system has been activated. In other words, multiple steady states of fire smoke transport could exist in a multi-branch tunnel.

Previous studies have noted the flow multiplicity in naturally ventilated single-space buildings (Hunt and Linden, 2000; Li and Delsante, 2001). The multiplicity of natural ventilation flow can be induced by the combined effects of stack pressure and the external pressure difference (wind or some other external driving force, e.g., a fan). A single stable flow state exists for the wind-assisted ventilation case, but multiple solutions exist for the wind-opposed case. The multiplicity of flow states in naturally ventilated buildings has not been restricted to single spaces. For a building that consists of interconnected spaces, the competition of the stack effect in a heated room and that in the unheated room could also lead to multiple steady flow states (Lin and Linden, 2002). Gong and Li (2013) noted the multiplicity of fire-induced smoke flow due to opposing buoyancy in two horizontally connected compartments. Gong and Li (2013) also investigated the effects of the height ratio of the two connected spaces on the smoke flow multiplicity. They found that there could be three

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http://dx.doi.org/10.1016/j.tust.2016.10.009
0886-7798/

Nomenclature

A	the cross-sectional area of the tunnel, m^2
c_p	the specific heat capacity, kj kg^{-1} k^{-1}
E	the convective part of the fire heat release rate, kW
g	gravitational acceleration constant, m s^{-2}
h_i	the height of branch #i, m
$\overline{H}$	the hydraulic diameter of tunnel, m
l	tunnel branch length, m
P_w	the total pressure of the exhaust fan, Pa
Q''	the dimensionless heat release rate based on the hydraulic tunnel diameter
Q_i	the flow rate of branch #i, m^3/s
Q_{iA}	upper smoke layer flow rate for branch #i, m^3/s
Q_{iB}	lower air layer flow rate for branch #i, m^3/s
s_i	flow impedance coefficients for the ith branch (i = 1–5), kg/m^7
s_{iA}	upper smoke layer flow impedance coefficients for the ith branch, kg/m^7
s_{iB}	lower air layer flow impedance coefficients for the ith branch, kg/m^7
T_a	ambient temperature, K
T_{1A}	smoke backflow temperature of branch #1, K
T_{2A}	smoke backflow temperature of branch #2, K
U	the tunnel wetted perimeter, m
V''	the dimensionless critical velocity based on the hydraulic tunnel diameter
V_c	ventilation velocity, m s^{-1}

Greek letters

ξ	local resistance coefficient
λ	friction factor
ρ_a	ambient air density, kg m^{-3}
ρ_{iA}	upper smoke layer density of branch #i, kg m^{-3}

Subscripts

A	upper smoke layer
B	lower air layer

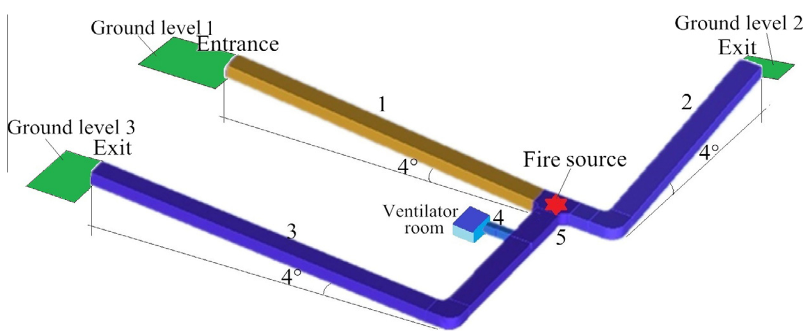

Fig. 1. Structural diagram of the multi-branch tunnel.

stable flow state solutions for the buildings with two horizontally connected compartments.

However, only limited research has been dedicated to the multiple steady states of fire smoke transport for an underground tunnel. For a naturally ventilated building, the multiplicity of flow states could cause a transition of ventilation patterns, e.g., transition from displacement ventilation to mixing ventilation, which could change the ventilation efficiency of the occupied zones. This situation becomes more complicated for a fire scenario and could cause more serious consequences. One-way traffic is usually employed in UTLTs. If the actual smoke flow route is different from the preset route (or the designed route) in a fire emergency, the smoke discharge route and the evacuation route could overlap, causing more casualties, especially in tunnels because the interfaces between the smoke layers and airflow in tunnels are much lower than those in tall buildings. In a multi-branch tunnel fire, the smoke movements inside the inclined tunnels could generate a stack effect. Operating the smoke exhaust system could cause the competition between the stack effects of different spaces or competition between the stack effect and the fan-induced pressure. In this paper, the multiple steady states of fire smoke transport in a multi-branch tunnel are investigated using both hydraulic analysis approach and numerical simulation. Then, the effects of the inclination angle of the connecting tunnels on the multiplicity of smoke flow are investigated.

2. An example tunnel case

2.1. Tunnel geometry

The multi-branch tunnel investigated by this study is part of an urban traffic tunnel system, which consists of one inlet tunnel, branch #1, two outlet tunnels, branches #2 and #3, and a main underground tunnel.

The schematic diagram of the multi-branch tunnel system is shown in Fig. 1. The length of branch #1 is 115 m, and the length of branch #2 is 102 m. The inclination angles of both branch #1 and branch #2 are 4 degrees. The total length of Brach #3 is 173 m. Branch #3 consists of a 125-m-long exit tunnel, with the inclination degree of 4°, and a 48-m-long horizontal main tunnel. Branch #5 is part of the main tunnel and is 20 m long. The tunnel portals are not located at the same ground level. The dimensions of the tunnel cross section are shown in Fig. 2. Branch #4 represents the ventilation duct connecting to the fan room; this branch is 15 m long with a cross section of 3 m × 3 m.

2.2. Fire source

Because the passing of heavy lorries is prohibited in urban traffic tunnels, the heat release rate, that corresponds to a car fire, 5 MW (Fire and smoke control in road tunnels, 1999), was