Tunnelling and Underground Space Technology 52 (2016) 85–98

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Innovative experimental reduced scale model of road tunnel equipped with realistic longitudinal ventilation system

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ARTICLE INFO

Article history:
Received 2 June 2015
Received in revised form 27 November 2015
Accepted 29 November 2015
Available online 14 December 2015

Keywords:
Road tunnel
Scaled model
Experimental model
CFD

ABSTRACT

Road tunnels require ventilation system for different reasons in order to provide a good level of safety and effectiveness in ordinary service and, in case of fire, to prevent the upstream smoke flow (back-layering phenomena). To evaluate the ventilation system, full scale experiments are more expensive both in terms of the costs and time, and the CFD model has high uncertainty without experimental validation. In this paper the authors have made and characterized experimentally a reduced scale impulsive jet fan in order to carry out a scaled longitudinal road tunnel subsection equipped with a realistic ventilation system. This innovative reduced scale model of road tunnel could give more relevant information such as phenomenology and performance of full-scale tunnel using suitable similarity rules. It could be useful to do parametrical studies or to focus on particular physical aspects (i.e. smoke pattern of thermal plume behavior with respect to usual experimental sections reported in literature). The innovative reduced scale model presented in this paper can provide a useful alternative method with respect to the full-scale experiments.

Moreover, the authors have simulated numerically, by means the CFD commercial software FLUENT®, the scaled road tunnel and have compared experimental and numerical results in terms of axial velocity.

1. Introduction

Road tunnels are often equipped with ventilation systems capable of providing a good level of safety, in particular to prevent the back-layering phenomena, i.e. the back of the smoke flow inside the road tunnel, to ensure safe evacuation in case of fire and to maintain the temperature value within acceptable limits. The study on smoke behavior in the road tunnel can carried out by means of full-scale model experiments that aim to obtain reliable indications on smoke flow pattern, temperature and visibility. They provide useful information to compare with experimental setup, numerical models and CFD simulations, but they are very expensive both in terms of costs and in terms of time.

The CFD analysis is a useful and powerful tool. It allows e.g. to examine different ventilation systems or fire scenarios or even the interaction among tunnel pattern, traffic and ventilation system, but it needs to be calibrated/validated on experimental data. In the absence of validation data, the comparative CFD analysis is a useful way of comparing the performance of different ventilation systems, as it is less affected by the lack of experimental data (Betta et al., 2009, 2010; Caliendo et al., 2013; Meng et al., 2014). Tang et al. report new findings for the distributions of smoke temperature and carbon monoxide for different pressure atmosphere (Tang et al., 2014). However, full scale experiments could give relevant information i.e. effect of fire location on flame characteristics and burning rate and radiation (Ji et al., 2015; Ingason et al., 2015a), large scale firefighting tests based on Water Spray System (Ingason et al., 2015b). Unfortunately, as highlighted by Ingason (Ingason, 2011), "the boundary conditions in large scale simulations such as wind at portals, air temperatures, lining surface" and the authors add ventilation system, "were usually not the most favorable for validation of advanced computer models. In the literature there are only few full scale experimental data and unfortunately they often do not correspond to the particular simulation that researchers intent to run".

The reduced scale model represents an alternative method to the full-scale experiment and numerical analysis. It can provide important information on phenomenology and performance to full-scale models, using suitable similarity rules and, moreover, it is useful to make parametrical studies or to focus particular physical aspects such as the smoke pattern plume behavior.

Oka and Atkinson (1995) have released an horizontal model tunnel, 1/10 scale of the Colliery tunnel, to study the systematic

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http://dx.doi.org/10.1016/j.tust.2015.11.025
0886-7798/

Nomenclature

c_p	specific heat, kJ kg^{-1} K^{-1}
D_H	hydraulic diameter, m
Δp	fan pressure drop, Pa
e	average velocity error, %
Fr	Froude number
g	gravity acceleration vector, m s^{-2}
G_b	generation of turbulence kinetic energy due to buoyancy, kg m^{-1} s^{-3}
G_k	generation of turbulence kinetic energy due to the mean velocity gradient, kg m^{-1} s^{-3}
h	tunnel height, m
i	index
k	turbulent kinetic energy, J/kg
L	characteristic length, m
N	number of cell along y-axes
p	pressure, Pa
Re	Reynolds number
S_{fan}	momentum source term, N m^{-3}
T	temperature, K
Y_M	contribution of the fluctuating dilation in compressible turbulence to the overall
v	dissipation rate velocity vector, m s^{-1}

Greek symbols

α	pitch angle, °
ε	turbulent dissipation rate, J kg s^{-1}
λ	scale factor
μ	turbulent viscosity, Pa s
ρ	density, kg m^{-3}
σ_k	turbulent Prandtl number for k
σ_ε	turbulent Prandtl number for ε

Subscripts

av	average
f	full scale tunnel
s	model scale tunnel
t	turbulent

smoke movement, using propane gas burners as fire sources, to examine the relationship between the fire heat release rate and critical velocity. Wu and Bakar (2000) have investigated the influence of tunnel slope on smoke movement through the tunnel model studied by Atkinson and Wu (1997) and have provided slope correlation factors for critical velocity. Roh et al. (2008) have used the Froude scaling method to conduct an experiment on 1/20 reduced-scale tunnel model, examining, for different ventilated conditions (natural and forced), the back-layering phenomena. Vauquelin and Telle (2005) have conducted an experimental study on a reduced scale 1/20 tunnel model. They have defined and evaluated the "total confinement velocity" as a new factor linked to the fire-induced smoke in order to extract the smoke completely. Ingason and Li (2010) have examined the critical velocity in the presence of blockage in a reduced scale 1/20 tunnel using the Froude method. Nyman and Ingason (2012) have used a CFD scale model for a longitudinal ventilation system to correlate the gas stratification and temperature distribution carried out in emergency case. Hu et al. (2013a, 2013b) have carried out tests in a reduced scale model tunnel to investigate the gas temperature and plume pattern; moreover Chen et al. carried out a new theoretically model, validated by means experiments conducted in a reduced-scale tunnel, to predict the smoke back-layering flow length. The numerical model included the factors of heat source-ceiling extraction and opening distances (Chen et al., 2015). Hu et al. (2006) studied, experimentally and numerically, the maximum ceiling gas temperature under the ceiling in a tunnel. They compared the CFD results with measured values and with those calculated using empirical equation. Ingason proposed an equation for predicting the position of the maximum ceiling gas temperature in a tunnel fire. He based the novel equation on a theoretical analysis and validated it using both laboratory test data and full-scale test data (Li and Ingason, 2014). The reduced scale tunnel has also used to study firefighting systems; Ingason has carried out study on 1:15 model scale tunnel with longitudinal ventilation using an automatic sprinkler system with glass bulbs (Li and Ingason, 2013). Blanchard et al. (2012) have studied the energy exchange during fire in tunnel in a 1/3 midscale model.

In above the all mentioned experimental studies, the ventilation air was supply by an external fan; therefore, the influence on flow provided by a jet fan was not took into account. In order to take into account the actual velocity profile downstream of the jet fan that is crucial in case of fire, Musto and Rotondo (2015) have numerically simulated full and reduced-scale tunnels in order to evaluate the possibility of carrying out a reduced scale road tunnel model with a realistic ventilation system of impulsive jet fans.

In this paper the authors have made and characterized by experimental test a reduced scale impulsive jet fan to create a scaled longitudinal tunnel equipped with a realistic ventilation system, that could be useful for researchers that intending to study the effects of a ventilation system on thermal plume and fire growth. The experimental scaled tunnel section, that is 1/25 scaled model of a subsystem (100 m) of a longitudinal tunnel 800 m length, is equipped with an impulsive jet fan. composed of an axial fan with an inner diameter of 28 mm, inlet/outlet silencers and flow conditioner.

The scaling procedure adopted was in accordance with Euler/Froude numbers preservation, allowing to analyze flow fields both in absence and presence of fire; the scale reduction 1/25 quite assures the turbulent conditions consistent with full scale model. Moreover, the authors have simulated the road tunnel numerically, by means of CFD commercial software FLUENT® (Fluent, 2005), and compared the numerical results with experimental ones.

2. Methodology

The choice of the reduction scale value has to assure the similitude between reduced and full scale models. The road tunnel under investigation is of a 1/25 reduced scale equipped with a longitudinal ventilation system as shown in Fig. 1. Due to periodic conditions across each jet fan, the authors investigated only a part of the domain. In this paper the study focused on a 100 m length part of the whole domain. In order to verify that the results provided by Road Tunnel Subsystem (RTS) could be extended to the Whole Road Tunnel domain (WRT) a methodology was proposed as shown in flowchart of Fig. 2.

In particular, Fig. 2 summarizes the methodology to create the experimental RTS equipped with realistic ventilation system. The methodology is divided into three steps. In the *first step*, a CFD analysis was performed on WRT domain (800 m) in order to obtain the boundary conditions to impose on the subsystem. The results carried out by a full scale RTS were compared with those provided by WRT. In the *second step*, the authors verified the feasibility of the