Tunnelling and Underground Space Technology 52 (2016) 38–43

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Numerical simulation of air ventilation in super-large underground developments

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ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form 22 October 2015
Accepted 17 November 2015
Available online 28 November 2015

Keywords:
Ventilation
Super-large underground development
Carbon monoxide
Dust

ABSTRACT

Recent advancements in engineering technology have enabled the construction of super-large underground engineering projects in China. Currently, the ventilation requirements and standards of normal-size underground spaces are used for super-large underground excavating engineering projects in China. For example, the minimum air velocity of 0.15 m/s is the standard velocity for normal-size underground spaces; however, this value is also used as the required air velocity for diluting underground contaminants in super-large underground developments. This paper aims to examine the minimum ventilation requirements for super-large underground developments ($S > 100\ \mathrm{m}^2$). A three-dimensional computational domain representing a full-scale underground space has been developed. The pertinent parameters such as dust concentration, smoke density, oxygen concentration and air temperature have been simulated. The results show that at some specific underground conditions, the ventilation air velocity of 0.15 m/s is sufficient to control the dust level, provide required oxygen concentration and maintain the air temperature at acceptable levels during development; however, it is not sufficient to bring the CO concentration below an acceptable safe limit. This must be considered by the ventilation system designers of super-large underground developments.

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1. Introduction

Recent advancement of engineering technology has enabled the construction of large-scale underground engineering projects in China. It is essential for designers of such projects to utilise correct ventilation practices and consider appropriate standard requirements. The ventilation performance of underground tunnels can be examined either by a full-scale experimental investigation, a reduced-scale test, or a numerical simulation. Of all these methods, the full-scale experimental investigation normally produces the most useful data since it is presumably reproducing the operational conditions of real situations. However, this method is costly and time-consuming. A numerical simulation, on the other hand, does not require expensive experimental facilities and instruments. It can be used to regenerate the real physical conditions; and if it is defined and validated properly can repeatedly analyse a problem under various conditions. Many researchers such as Gosman (1999), Parra et al. (2006), Migoya et al. (2009), Colella et al. (2011), and Montazeri (2011) have carried out experimental and numerical simulations to study three-dimensional geometries with various flow and thermal conditions. They found a good agreement between their numerical and experimental results. The commercial software package ANSYS-FLUENT has commonly been used by many researchers to study various fluid-flow and heat transfer problems. Yuandong and Zhonghua (2013) demonstrated a good agreement between their numerical results for the airflow and pollutant dispersion and the experimental results obtained by Rafailidis and Schatzmann (1995) on a detailed wind tunnel study.

In terms of numerical simulation studies of underground engineering, some researchers have conducted studies on underground transport tunnels (Jain and Kumar, 2011; Kim and Kim, 2009; Juraeva et al., 2013) and underground car parks (Xue and Ho, 2000; Viegas, 2010). Other researchers have conducted numerical simulation of underground mine environments (Gao et al., 2002; Parra et al., 2006; Hargreaves and Lowndes, 2007; Toraño et al., 2009; Zheng, 2011; Torno et al., 2013; Zhongwei and Ting, 2013). Some of the reported numerical studies on operating ventilation systems in underground environments have focused on dust management. Wei et al. (2011) used the gas–solid two-phase flow

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http://dx.doi.org/10.1016/j.tust.2015.11.009
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theory to predict dust distribution and movement at the work-face in an underground mine environment. They compared their results with the observed data from an actual work-face. Toraño et al. (2011) studied the dust behaviour under two auxiliary ventilation systems by using three-dimensional models. They determined dust concentrations at different cross-sections of an operating coal work-face. Ren et al. (2014) simulated the airflow and respirable dispersion patterns along the belt roadway to assist in the design of a better dust mitigation system. They also discussed ways for reducing the respirable dust concentration.

"Construction specifications on underground excavation engineering of hydraulic structures" developed by the Ministry of Water Resources of the People's Republic of China (2007) is currently used for the development of normal-size tunnels, roadway excavations and other underground facilities in China. These standards are also used by the designers of super-large underground excavating engineering with huge cross-sectional areas ($S > 100\ \mathrm{m}^2$) in order to minimise the investment and operational costs of environmental and ventilation control systems. For example, the minimum air velocity of 0.15 m/s, recommended for normal-size tunnels, is used for calculating the ventilation requirements of large-scale underground spaces. The main concern is to whether this velocity can meet the safety requirements for diluting blasting gases, removing dust and controlling the air temperature at the work face. This study has been undertaken to examine the ventilation performance of super-large underground excavating engineering projects and determine the minimum ventilation requirements.

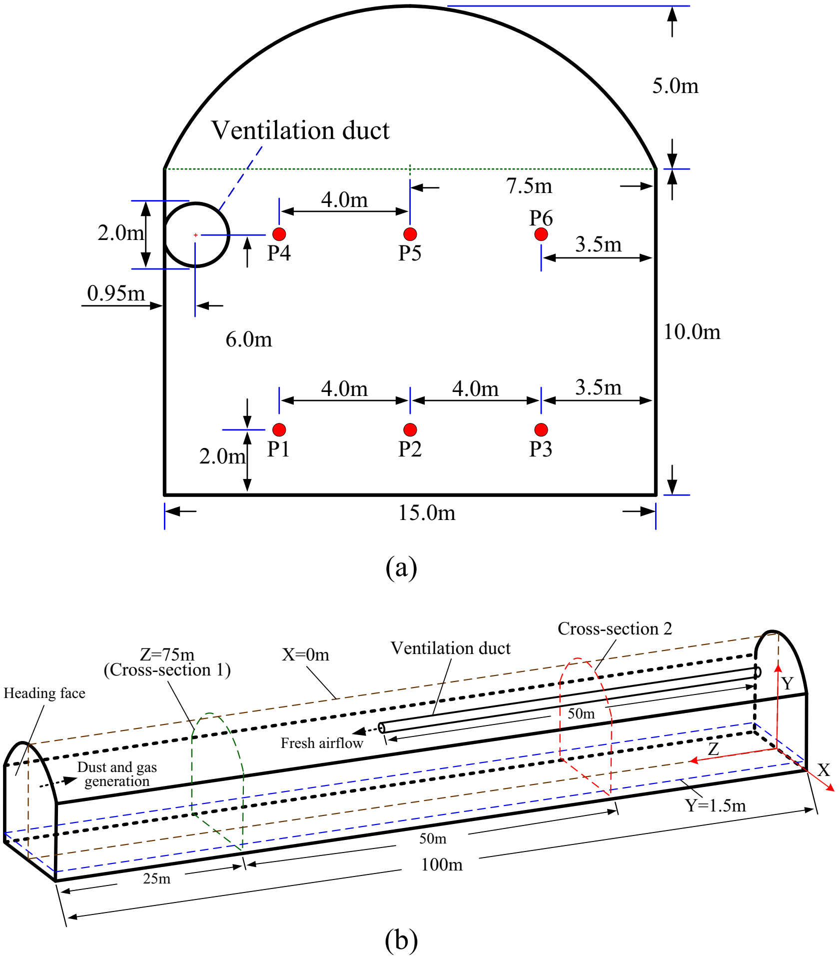
2. Numerical analysis

2.1. Methodology

The numerical model used in this study is based on solving the differential equations of conservation of mass, momentum and energy, and is complemented by turbulent flow models. Calculations are performed with the commercial software package ANSYS-FLUENT. This code uses the finite volume method and solves the three-dimensional Navier–Stokes equations on an unstructured grid. The turbulence is simulated with the standard k–ε model. The species transport model is used to simulate the variation of the CO and O_2 mass faction. The mass fraction of each species, Y_i, is calculated using a convection–diffusion equation for the i species. The conservation equation and mass diffusion in turbulent flows can be presented in the following general forms:

$$\begin{cases} \frac{\partial}{\partial t}(\rho Y_i) + \nabla\cdot(\rho\vec{v}Y_i) = -\nabla\cdot\vec{J}_i + R_i + S_i \\ \vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\nabla Y_i - D_{T,i}\frac{\nabla T}{T} \end{cases} \qquad (1)$$

where R_i is the net rate of production of species i, S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources, $\vec{J}_i$ is the diffusion flux of species i, $D_{i,m}$ is the mass diffusion coefficient for species i, $D_{T,i}$ is the thermal diffusion coefficient, Sc_t is the turbulent Schmidt number, μ_t is the turbulent viscosity, D_T is the turbulent diffusivity, ρ is the fluid density, $\vec{v}$ is the average flow velocity, ∇ represents the gradient and $\nabla\cdot$ represents the divergence.



(a)

(b)

Fig. 1. Schematic diagram of underground excavation engineering project: (a) Cross-sectional view of underground development and test points. (b) Three-dimensional view of computational domain.

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