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An alternative algorithm of tunnel piston effect by replacing three-dimensional model with two-dimensional model

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ABSTRACT

With the rapid development of the underground railways in China, the subway has become an increasingly important mode of transportation. Owing to the significant influence piston wind has on tunnel ventilation, piston wind has gained much attention from researchers. At present, the most common method for this research is a three-dimensional Computational Fluid Dynamics (CFD) simulation. However, the three-dimensional model has its inherent characteristics. Large number of grid quantities, long calculation times, significant computational requirements and high technical personnel requirements all influence the development of the three-dimensional model applied into the practical engineering. This study aimed to simplify the complicated three-dimensional model by creating a simple two-dimensional dynamic mesh model while ensuring the accuracy of the simplified simulation results. In order to explore suitable alternative methods, six types of two-dimensional simulation models are suggested in this study. Firstly, in order to prove the accuracy of the dynamic mesh simulation method, the CFD simulation results were validated with experimental results. Secondly, the six alternative methods were applied to the experimental model, full-scale model, train passing through a tunnel model, and subway station model in order to determine the best two-dimensional method. Finally, grid number, calculation time, and internal storage usage between the two-dimensional simulations and the three-dimensional simulation were evaluated, and these results demonstrated the superiority of the two-dimensional simulation model.

1. Introduction

In recent years, urban railway transit has developed rapidly in China. Because of the adverse ventilation conditions, increasing attention is being paid to underground tunnel and subway station ventilation systems [1]. Research has indicated that the air in a subway tunnel can be approximately eight times more genotoxic and four times more likely to cause oxidative stress in human lung cells than the air in an urban street if the tunnel is not adequately ventilated [2]. Therefore, ventilation system is very important to the tunnel. Owing to its specific length-width ratio, the piston wind generated by a train moving through the tunnel has a significant impact on the tunnel ventilation and environment. Piston wind can strengthen the tunnel ventilation and purify the tunnel environment, but it will be detrimental if the design of tunnel ventilation system was not using piston wind. Moreover, excessive piston wind will give people a bad train experience. Therefore, an increasing number of researchers are focusing on piston wind in tunnels. Wang et al. [3,4] have studied unsteady piston wind in multiple stacks. A previously developed hot wire technique was used to obtain both mean and instantaneous flow characteristics. Zhang et al. [5] used mathematical modeling and sensitivity analyses to analyze the influence of the piston wind on a subway tunnel. As a result, a universal prediction formula to estimate the ventilation effect of piston wind was suggested. The wind speed and wind direction produced during operation of mechanical ventilation were considered by Zhou et al. [6] along with those resulting from piston wind and natural wind in the tunnel as part of an analysis of the temperature field distribution in a railway tunnel. Liu et al. [7] studied pressure variations caused by piston wind from high-speed trains passing through the tunnels. Wang et al. [8] studied the influence of piston wind on particulate matter concentrations. As this demonstrates, research into tunnel piston wind has become increasingly important.

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Nomenclature

u_i	the velocity component in i direction
x_i	the coordinate component in i direction
k_t	turbulent thermal conductivity
μ_T	turbulent viscosity
G_k	the generation of turbulence kinetic energy due to the mean velocity gradients
G_b	the generation of turbulence kinetic energy due to buoyancy
Y_M	the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
k	turbulent kinetic energy
ε	dissipation rate of turbulent kinetic energy
ρ	molecular density
D	hydraulic diameter
A	cross-sectional area
P	wetted perimeter
PPMCC	Pearson's product–moment correlation coefficient
E_i	test value
S_i	simulation value
$\overline{E}$	average test value
$\overline{S}$	average simulation value
MBE	Mean Bias Error
B_i	two-dimensional simulation value
C_i	three-dimensional simulation value
l	train length in two-dimensional model
w	train width in two-dimensional model
L	tunnel length in two-dimensional model
W	tunnel width in two-dimensional model
L'	station length in two-dimensional model
W'	station width in two-dimensional model

Experimental analysis and numerical simulation are two important research methods for the study of piston wind. Kim and Kim [9] analyzed train-induced unsteady flow in a subway tunnel. Experimental analysis of piston wind was conducted using a 1:20 scale model tunnel. Zhang et al. [10] studied the effects of oblique tunnel portals on train and tunnel aerodynamics using a 1:20 scale moving model. The results indicated that oblique tunnel portals had significant mitigation effect on the pressure gradient and micro-pressure wave generated by the model train passing through the model tunnel. Riccoa et al. [11] conducted laboratory experiment in a scaled facility in which train models travelled at a maximum velocity of approximately 150 km/h through a 6 m long tunnel. The pressure waves generated by a train was explored. However, the experimental method used for tunnel research is often difficult. The test bench can be difficult to build and these experiments have significant requirements for the outside wind environment. Therefore, the experimental method has been used infrequently. Wang et al. [12] conducted field measurements in a real tunnel. However, these measurements are not always permitted and the working conditions may be unacceptable.

Numerical simulation is widely applied in tunnel research, and can be separated into one-dimensional, two-dimensional, or three-dimensional simulations. Lin et al. [13] studied piston effects on underground tunnel ventilation influenced by a draught relief shaft. The one-dimensional model of the Subway Environmental Simulation (SES) program was used to simulate the piston wind volume in the tunnel. Tong et al. [14] established airflow and contaminant equations and solved them for steady state assumptions using a one-dimensional simulation. Although the computing speed was fast, the one-dimensional model was only able to calculate the total air volume of the cross-section. Velocity distributions cannot be obtained with a one-dimensional simulation. With the development of computer simulation technology, Computational Fluid Dynamics (CFD) was adopted by more and more scholars to research many environmental areas, including outdoor wind distribution [15], indoor air quality [16], and tunnel ventilation. Huang et al. [17,18] adopted three-dimensional model with a dynamic layering method for the investigation of the characteristics of train-induced unsteady airflow in a subway tunnel with natural ventilation ducts. This model was also used to analyze the effect of solid particulates on duct ventilation performance in a subway tunnel. The length of the model in that study was 39 m. Chu et al. [19] conducted a series of three-dimensional numerical simulations in order to examine the influence of tunnel length, blockage ratio, train speed, and intersection locations on the interactions of aerodynamic waves generated by trains. Ogawa and Fujii [20] carried out three-dimensional computations for the flow field produced when a train moves into a tunnel. Xue et al. [21] used CFD to analyze the three-dimensional unsteady airflow in a tunnel and subway station. A three-dimensional simulation model provides comprehensive results. However, the three-dimensional simulation has a huge number of grid and long calculation times. In addition, it required a high-performance computer. In practical application, the three-dimensional simulation is not applicable if a project is under time or resource constraints. It would impact the project progress. Furthermore, the three-dimensional simulation needs a person who has a high professional skill level. The researchers might employed three-dimensional model to obtain a more accurate model. However, the three-dimensional simulation was inconvenient in practical applications.

Some scholars have combined one-dimensional and three-dimensional models to explore unsteady piston wind and the tunnel environment [22,23]. However, two-dimensional methods were less commonly used in research because it is difficult to confirm the size of a two-dimensional model to replace the three-dimensional model. Choi and Kim [24] studied the aerodynamics of a subway tunnel with a two-dimensional axisymmetric model using CFD. Yang et al. [25] simulated a two-dimensional CFD model in order to study the piston wind velocity during the arrival and departure of subway trains at a station. However, the method for building the two-dimensional model was not involved in either study. Therefore, a method to confirm the model size and to use a two-dimensional model to replace a three-dimensional model accurately is a worthwhile subject to examine. Different from one-dimensional model and three-dimensional model, two-dimensional simulations can not only obtain the velocity distribution, but also have short calculation time. It will provide much more convenience to the practical application.

This paper aimed to find an alternative method using a two-dimensional model to replace a three-dimensional model for more convenient tunnel research. The three-dimensional dynamic mesh simulation method in this study was validated by experimental results. In addition, six types of two-dimensional model were suggested. Comparisons were conducted between the two-dimensional models and three-dimensional model for the experimental conditions, conditions representing an actual long tunnel, and conditions of a train passing through the tunnel. The most accurate method to replace the three-dimensional simulation was determined. This alternative method was applied for subway station conditions and a suitable two-dimensional model was also determined. Two-dimensional simulations have significant advantages over three-dimensional simulations in terms of grid number, simulation time, computer performance and technical personnel requirement. It may be of great benefit to tunnel research and practical engineering.