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Influences of the train-wind and air-curtain to reduce the particle concentration inside a subway tunnel

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ABSTRACT

Subways are used widely for public transportation in major cities and require efficient ventilation systems to maintain indoor air quality in the subway tunnel. A subway tunnel was investigated numerically and experimentally to reduce the particle concentration in subway tunnels. The subway tunnel is 54-m long, 1.65-m high, and 2.5-m wide. The subway tunnel is one-quarter scale of a real subway tunnel. The tunnel has two U-type mechanical ventilation shafts. The steady three-dimensional airflow in the tunnel was analyzed using ANSYS CFX software to solve the Reynolds-averaged Navier–Stokes equations. The airflow in the tunnel and shafts was observed numerically using the train-wind and air-curtain. The effects of the train-wind, air-curtain, and electric precipitator were examined experimentally. The ventilation performance in the subway tunnel was observed with respect to the particle concentration in the tunnel. The numerical results suggest proper operating conditions for experimental analysis of the particle concentration. The average velocity of the airflow increases in the shaft when the velocity of the air-curtain increases. The particle concentration at the dust monitoring device after ventilation shaft 1 was reduced significantly in the tunnel when the air-curtain and train-wind were operated.

1. Introduction

Subways are widely used public transportation systems which require proper ventilation systems to maintain the indoor air quality (IAQ) in a subway environment. Subways are enclosed spaces, and the air quality deteriorates due to air pollutants emitted from moving trains, as well as particles brought in by passengers and ambient air through ventilation. The air in a subway tunnel is approximately eight times more genotoxic and four times more likely to cause oxidative stress in human lung cells than the air on an urban street (Karlsson et al., 2005). Additionally, the fine particle concentration is higher (Aarnia et al., 2005).

Platform screen doors (PSDs) are installed in subway stations to improve environmental conditions in the station. The PSD provides highly effective controls for heating, ventilation, and air-conditioning (Kim et al., 2012) and is beneficial for improving the air quality on a subway platform, but it degrades the air quality in tunnels while reducing ventilation by the train-wind. The particulate matter (PM) level is higher in a subway tunnel than on the subway platform. The major chemical species in the subway are Fe-containing, carbonaceous, soil-derived particles, and aerosols such as nitrates and sulfates. The indoor air of a subway contains PM of heavy metals generated from the friction of wheels and brake pads, and gaseous nitrogen and sulfur oxides are abundant in the indoor subway environment. The station IAQ becomes worse due to the high concentrations of fine dust from the tunnel, which is transported into the subway platform by trains (Song et al., 2008).

The ventilation systems in subway tunnels, including train-induced airflow, require investigation. Experimental and numerical studies were performed to analyze the unsteady three-dimensional flow in a subway tunnel with a single track (Modic, 2003; Ogawa and Fujii, 1997). Environmental protection and public safety are the main reasons for tunnel ventilation (Li and Chow, 2003). Train-induced airflow in tunnels with more than one track was examined both numerically and experimentally. Experimental studies of the effects of moving vehicles on tunnel ventilation were performed for two trains moving in the same and opposite directions (Chen et al., 1998). The airflow is not sufficient to push the pollutant air out of the tunnel when two trains run in opposite directions. Numerical simulations were performed to analyze the airflow in a subway twin-track tunnel (Li et al., 2006; Waymel et al., 2006).

Subway tunnels and ventilation systems were constructed many years ago and are susceptible to dust generation.

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High-performance trains continuously generate heat and dust that exceed the amounts that can be removed by piston-effect ventilation. The airborne radon levels in the subway cabins were increased by 53% after PSD installation in a subway station (Jeon et al., 2012). Radon is a colorless, odorless, and tasteless gas produced by the radioactive decay of uranium and thorium, and its products are human health hazards. Adequate subway ventilation is needed to maintain the IAQ in a subway.

A subway tunnel was constructed for experimental and numerical studies to improve the ventilation performance in a tunnel. The purpose of this study was to reduce the particle concentration in the subway tunnel. The airflow velocity in the tunnel and ventilation shafts with the train-wind and air-curtain were examined numerically using ANSYS CFX software by solving the Reynolds-averaged Navier–Stokes equations (ANSYS CFX, 2009). The effects of the train-wind, air-curtain, and electric precipitator were observed experimentally. Numerical and experimental analyses were used to identify the proper conditions for the electric precipitator operation to decrease the particle concentration.

2. Analysis procedure: numerical and experimental approach

2.1. The model subway tunnel

The subway tunnel was constructed at one-quarter scale with respect to a real subway tunnel. The tunnel under consideration is straight, 54-m long, 1.65-m high, and 2.5-m wide, and it has no stations. The subway tunnel was built to do experiment. The tunnel has three U-type mechanical ventilation shafts and is one-quarter scale of a real subway tunnel as shown in Fig. 1. Ventilation shaft 1 was installed at 5 m from the tunnel inlet, and ventilation shaft 2 was installed 20 m from the tunnel outlet. Ventilation shaft 1 was connected to the side of the subway tunnel, and ventilation shaft 2 was connected to the top of the subway tunnel. The U-type mechanical ventilation shafts have two ducts with an axial flow fan. The pollutant air was discharged through the axial flow fan 1 of each ventilation shaft, and clean air was entered the tunnel through the axial flow fan 2 of each ventilation shaft. An air-curtain was installed between the ducts of the ventilation shaft of the subway tunnel (Gupta et al., 2006). The thickness and length of the air-curtain were fixed to 0.1 m and 1.4 m, respectively. The guide vane was installed at the end of the ducts of the ventilation shafts. The installation angle of the guide vane was 60°. Each ventilation shaft has two axial flow fans: one to discharge airflow from the tunnel and one to supply the air to the tunnel. The electric precipitator in the middle of each ventilation shaft has filtering media with an effective filtration process. The train-wind (wake flow) was generated using an axial flow fan at the tunnel inlet.

2.2. Numerical analysis

2.2.1. Computational tools and turbulence model

ANSYS CFX software consists of Workbench which includes Design Modeler, CFX-Pre, CFX-Solver, and CFX-Post. The Design Modeler provides the geometry and modifies the geometry read-through data formats. Computational fluid dynamics was used to predict the ventilation performance in the tunnel (Chen, 2009). Standard two-equation turbulence models often fail to predict the onset and amount of flow separation under adverse pressure gradient conditions, whereas the k–ω-based shear stress transport model was designed to make highly accurate predictions of the onset and amount of flow separation under adverse pressure gradients by the inclusion of transport effects into the formulation of the eddy viscosity (Menter, 1994). The choice of the turbulence model depends on considerations such as the flow physics, including massive flow separations, established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of computing time available for the simulation. The computational results were obtained using parallel PCs (cluster system: Core 2, Quad 2) running on a Linux operating system.

2.2.2. Numerical analysis: computational grid validation and boundary conditions

The computational grid of the model subway tunnel was generated using an unstructured grid. A dense grid was distributed around the wall, air-curtain, and guide vane of the tunnel. The grid was distributed along the three axes. A grid validation study was performed to ensure that the computed quantities would properly converge. The numerical method was validated with one mechanical ventilation shaft in a 20-m-long straight tunnel. The number of elements in the tetrahedral mesh under consideration was between 850,000 and 1,600,000. The airflow passing through the shaft was measured in the tunnel.

The grid convergence test results indicated that the proper number of elements for the tunnel flow study at which the mass flow rate converges to an almost constant value was approximately 1,000,000, as shown Table 1. The minimum grid size was 0.001 m, and the maximum grid size was 0.01 m based on the converged solutions. The train-induced air velocity predicted by the numerical analysis agrees reasonably well with the experimental measurements at the five measurement points between the tunnel inlet and ventilation shaft 1 (Final report, 2010). The velocity distributions at the measurement points provided similar results. The velocity distributions of the numerical and experimental analysis were uniform along the tunnel. The velocity at the center point of the tunnel (point 5) was higher than those at the other measurement points along the tunnel due to the viscous flow effect in the boundary layer near walls. The correlation coefficient between the experimental and numerical results is 0.9301 and it is the positive direction and strong correlation.

A numerical computation was performed without train runs. The working fluid was air at 25 °C under atmospheric pressure. The adiabatic wall boundary condition was used for the tunnel walls, as shown in Table 2. All walls were treated as viscous surfaces with no-slip velocity conditions. The opening conditions were imposed at the inlet and outlet of the subway model tunnel for flow analysis without a train-wind. The axial flow fans were not operated in the computation. However, the boundary conditions for the fans were prescribed at the surface as like as fans were

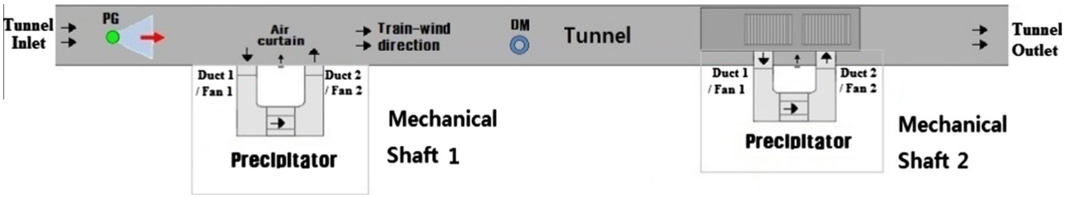

Fig. 1. The schematic view of the model subway tunnel.