

Ventilation Efficiency in the Subway Environment for the Indoor Air Quality

Kyung Jin Ryu, MakhsudaJuraeva, Sang-Hyun Jeong and Dong Joo Song

Abstract—Clean air in subway station is important to passengers. The Platform Screen Doors (PSDs) can improve indoor air quality in the subway station; however the air quality in the subway tunnel is degraded. The subway tunnel has high CO₂ concentration and indoor particulate matter (PM) value. The Indoor Air Quality (IAQ) level in subway environment degrades by increasing the frequency of the train operation and the number of the train. The ventilation systems of the subway tunnel need improvements to have better air-quality. Numerical analyses might be effective tools to analyze the performance of subway twin-track tunnel ventilation systems. An existing subway twin-track tunnel in the metropolitan Seoul subway system is chosen for the numerical simulations. The ANSYS CFX software is used for unsteady computations of the airflow inside the twin-track tunnel when the train moves. The airflow inside the tunnel is simulated when one train runs and two trains run at the same time in the tunnel. The piston-effect inside the tunnel is analyzed when all shafts function as the natural ventilation shaft. The supplied air through the shafts is mixed with the pollutant air in the tunnel. The pollutant air is exhausted by the mechanical ventilation shafts. The supplied and discharged airs are balanced when only one train runs in the twin-track tunnel. The pollutant air in the tunnel is high when two trains run simultaneously in opposite direction and all shafts functioned as the natural shaft cases when there are no electrical power supplies in the shafts. The remained pollutant air inside the tunnel enters into the station platform when the doors are opened.

Keywords—indoor air quality, subway twin-track tunnel, train-induced wind

I. INTRODUCTION

SUBWAY system plays much more important role as public transportation than bus, passenger car and taxi. Efficient ventilation is needed to maintain good Indoor Air Quality (IAQ) in subway environment. The fine dust which makes the IAQ worse is frequently transported into platform by subway trains [1]. Ventilation design studies in subway ventilation systems are performed numerically by predicting various parameters such as vehicle emission dispersion, visibility and air velocity [2], [3]. Air in a subway tunnel is affected by temperature, humidity, air velocity and a variety of pollutants. Numerical simulations of subway tunnel ventilation mainly focused on emergency situations such as fire conditions [4]. An installation of Platform Screen Doors (PSDs) improves the efficiency of ventilation systems and air-conditioning.

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PSDs reduce noise and wind blasts caused by a train and improve safety and comfort within the platform environment [5]. The air in the platform is significantly affected by the train-induced airflow. The PSDs improve the IAQ in subway platform; however, degrades the air quality in tunnels while reducing ventilation by the train-induced airflow. The tunnel has much higher CO₂ concentration and indoor particulate matter (PM) value than the platform. The dust is accumulated in the tunnel. The factors for the subway tunnel IAQ are classified into three: ferrous, outdoor source and soil related. The subway tunnel has higher ferrous related concentrations than the platform [6]. The factors influencing IAQ are station structure, ventilation and passengers in the subway. Proper ventilation system design is essential in maintaining acceptable air quality inside the subway tunnel. Thus optimum ventilation systems are required for subway tunnel and platform to protect the subway environment.

Computational Fluid Dynamics (CFD) is applied to simulate the subway ventilation systems. The ventilation systems of the tunnels and the aerodynamics of the moving train through the tunnel systems are analyzed by using ANSYS CFX software [7]. Numerical simulations show ventilation system performance and effectiveness. This study will help us to understand the behavior of the air pollutants and provide us guidelines for good IAQ in subway environment. An existing subway twin-track tunnel is observed to analyze ventilation performance inside the tunnel when a train moves. Air pollutants inside the tunnel are governed by the aerodynamics in the tunnel. The piston effect under normal one train operation in the subway tunnel is very small and train-induced airflow forms circulation inside the tunnel.

II. NUMERICAL ANALYSIS

A. Existing subway tunnel

The existing subway twin-track tunnel in the Seoul metro subway system is used as the computational domain. The computational domain of the tunnel is a real scale of the existing subway. The domain is simplified for the easy numerical analyses of the train-induced airflow with the PSDs installed stations. The computational domains of the subway tunnel are consisted of solid and fluid domains. The train is a solid domain while the tunnel air is a fluid domain. The domain has a natural ventilation shaft, two mechanical ventilation shafts, a mechanical air-supply and a train as shown in Fig. 1. The PSDs installed stations are about 200 m long each. The twin-track involves running one train in each direction. The train is 200m long, about 5m high and 3.5 m wide. The total length of the domain is about 1845 m. This length includes a 1045 meter section of tunnel between station A and station B. The domain includes 200 m for each PSDs installed station and 200 m for additional tunnel space on each side of the station.

The additional tunnel space is needed to determine the influence of the train-induced airflow. The tunnel is about 6.2 m high and 4.5 m wide. The unsteady time accurate computations are made when the train runs on track 1 from station A to station B. The twin-tracks are separated by blocks, the blocks are 1.5 m long and each block is separated by 3 m distance.

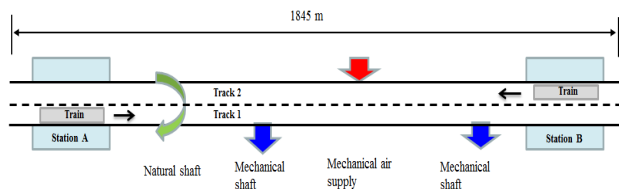


Fig. 1 Schematic view of the existing subway tunnel

B. Analysis: Turbulence model and computational tools

ANSYS CFX software consists of Workbench, CFX-Pre, CFX-Solver and CFX-Post. The ANSYS Workbench provides the geometry, modifies the geometry read-through data formats. The external ICEM-CFD software combines the graphical user interface for all the separate geometry, meshing, includes surface modeling and grid generation including hybrid grids. The computational grid is generated by structured grid of ICEM-CFD. Table 1 shows the grid number and the velocity from the grid validation study. The grid is distributed along three axes. A grid validation study is performed to make sure that the computed quantities are properly converged. Dense grids are generated near the wall of the tunnel. The grid size in the tunnel length is set to between 0.0025m - 0.72m in z direction, i.e., train moving direction. In the cross-section of the tunnel it is between 0.025m - 0.25m in x direction and between 0.03m - 0.28m in y direction.

The immersed solid method of ANSYS CFX is suitable for a numerical modeling of the moving boundary in subway [8]. Standard two-equation turbulence models often fail to predict the onset and the amount of flow separation under adverse pressure-gradient conditions, while the $k-\omega$ based Shear Stress Transport model was designed to give highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients by the inclusion of transport effects into the formulation of the eddy-viscosity [9]. The time derivative terms are discretized for time accurate unsteady

computations. The choice of the turbulence model depends on considerations such as the flow physics including massive flow separations, the established practice of 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 are obtained using parallel PCs running Linux operating system. A velocity measurement device, i.e., velocity transducer is installed in the existing subway tunnel between the natural and the first mechanical shaft [10]. The comparison of air velocity between the computational analysis and the experimental measurement is made with time at measured location. The computed velocity at the location agrees reasonably well with the experimental result.

C. Simulation conditions for the subway tunnel

On the solid walls of the train and the tunnel body, the viscous adiabatic surface with a no-slip velocity boundary condition is applied as given in Table 2. The mechanical ventilation shaft and the mechanical air-supply have two separated ducts for operating axial flow fans. Opening conditions are imposed at the exit of the shafts and the tunnel ends. The opening boundary condition is used when the tunnel ends are open and the wall condition is applied when the tunnel ends are closed. The subsonic outlet boundary conditions are used at fan outlets of mechanical shafts and inlet condition is applied at the fan inlet of the mechanical air-supply. The natural ventilation shaft of the tunnel discharges the airflow out or supplies airflow through the shaft depending on the train-induced effect. The mechanical ventilation shaft discharges the induced-airflow out through two installed axial flow fans in the ducts (capacity: $\Delta p=400\text{Pa}$ each). The air enters into the tunnel through the mechanical air-supply by two installed axial flow fans in the ducts (capacity: $\Delta p=700\text{Pa}$ each) and through the tunnel ends. The physical time step of unsteady analysis is 0.04 s and total computational time is 105 s. The separated flows and recirculation flows can be seen with this time step. The computational results are obtained using parallel PCs (Cluster system: Core i7, RAM 8GB, 4 PCs) running Linux operating system. The computation time is about 300 hours for one full unsteady computation from the beginning to the end. The working fluid is air at 25°C under atmospheric pressure condition. The train speed is imposed on the train domain and is set by using user defined function. The train domain moves into the fluid domain with the specified train speed. The train accelerates linearly until 24.4 s and passes by the first mechanical ventilation shaft with constant speed. The train starts to decelerate linearly at 48.2 s and stops at 105 s completely.

III. RESULTS AND DISCUSSION

The tunnel aerodynamics mainly deals with the performance of the ventilation systems with a moving train inside tunnel. The moving train can induce airflow by pushing and shearing local surrounding air. The train-induced airflow or wake is generated by the moving train in the tunnel. The wake flows massively in the train moving direction. The induced airflow

TABLE I

GRID CONVERGENCE TEST: AVERAGE COMPUTED VELOCITY AT VARIOUS NUMBER OF GRIDS

Grid number (million)	Velocity (m/s)
0.6	13.3434
1.16	13.0964
2.16	11.3165
3.23	11.2787
5.55	11.2598

delivers and exchanges the air between the stations and the tunnel. The amount of exchange between the tunnel air and the station air influences subway environment significantly, including temperature, humidity and IAQ. The air exchange implies the demand of the ventilation for the tunnel pollutant air. The fresh air is supplied into the subway tunnel by the mechanical air-supply and the natural shaft. The mechanical air-supply is located between the mechanical shafts. The pollutant air is discharged through the natural and the mechanical shafts. The ventilation system in the subway has an important function to supply fresh air into the subway and to discharge air-pollutant from the subway.

TABLE II
THE BOUNDARY CONDITIONS OF THE COMPUTATIONAL DOMAIN

Boundary condition	Location	Value
Inlet	fan inlets	700 [Pa] + 700 [Pa]
Outlet	fan outlets	400 [Pa] + 400 [Pa]
Opening	tunnel ends, natural shaft exit, mechanical shafts exit	0 [Pa]
Wall	tunnelbody, train body	no-slip, adiabatic

A. Influence of the natural ventilation on the tunnel ventilation performance

The natural ventilation shafts discharges the airflow due to the piston-effect. All ventilation shafts in the computational domain can function as the natural ventilation shafts. There are no electrical power supplies in shafts when shafts function as natural ventilation shafts. This computation investigates the influences of the piston-effect on the ventilation when the train runs in the track 1. The discharged flow in the ventilation shafts changes rapidly to the supply flow, as the train passes each ventilation shaft. The airflow velocity at the natural ventilation shafts increases as the train approaches the shafts and it reaches its peak when the tail of the train passes the natural ventilation shafts. The supplied-air into the tunnel is more than the discharged-air at the natural shaft. The massive supplied air through the shafts is balanced by the discharged air through shafts ahead of the natural shaft in train passing direction. The airflow velocity at the natural ventilation shaft decreases gradually as the train passes the shaft. The airflow velocity in the tunnel is mainly induced by the shafts, the piston effect and wake flow of the moving train. The supplied and discharged air is not well balanced. The supplied air pushes the pollutant air and they are mixed in the tunnel. The air moves toward to the station and enters into the station platform area as PSD opens. The stations need the air quality improving tools such as electrostatic precipitators, air-curtain, a barrier, and etc. [11], [12].

B. Effect of a train running in the twin-track tunnel on the ventilation performance

The train-induced airflow due to one train running in the tunnel moves through track 1 and enters the neighboring track 2 between the blocks. The aerodynamic analyses of unsteady flowfields are essential to understand the airflow behavior inside the twin-track tunnel. The supplied air mixes with the pollutant air in the tunnel and the mixed pollutant air is pushed toward the stations by the induced airflow. Dispersion of gaseous pollutants is dominated by the massively induced airflow in the tunnel. The pollutants are transported along with the airflow behind and around the moving train. Bigger particles fall back to the ground rapidly while the fine particles remain floating in the air. The pressure difference formed by the moving air around and behind the train lifts fine particles. The pollutant air inside the tunnel is discharged using axial flow fans at both ducts of the mechanical ventilation shafts to provide a suitable environment for passengers.

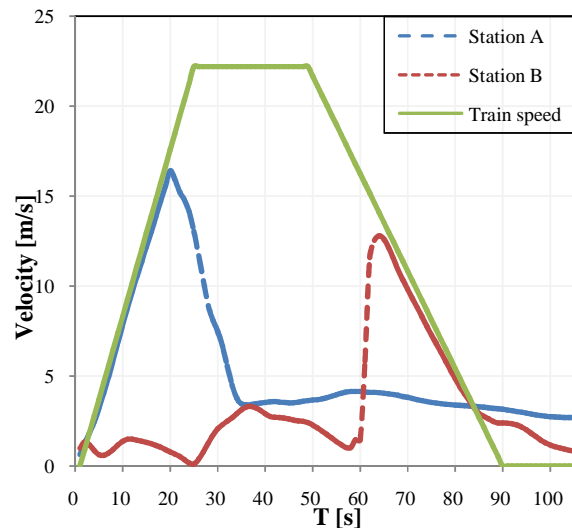


Fig. 2 Temporal variation of velocity at the station A and B with the train speed

The discharged airflow through the exit of the shaft increases as the train approaches the shaft. High velocity occurs at the exits of the mechanical ventilation shaft due to piston effect. Figure 2 shows temporal variation of average velocity at the stations A and B due to the piston-effect. The airflow velocity behind the train increases as the train accelerates and decreases rapidly as the train runs with constant speed in the station A. The airflow velocity at the station B increases after the train decelerates and approaches to the station B.

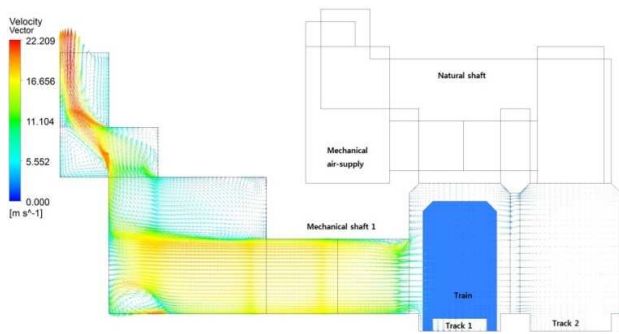


Fig. 3 Local velocity of the discharged airflow at the exit of the shaft 1 as train approaches the mechanical shaft 1

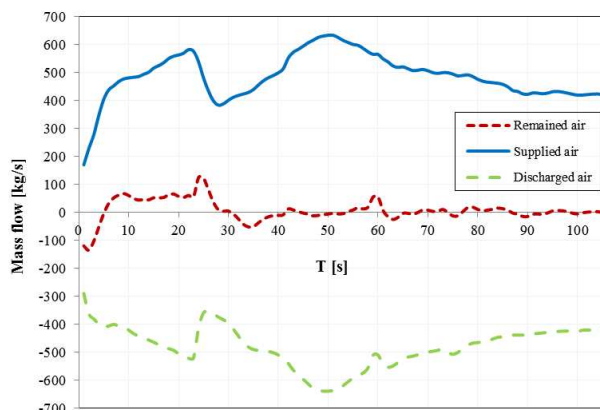


Fig. 4 The airflow balance when the train runs in the track 1

Figure 3 shows velocity vector plot at the mechanical shaft 1 as the train approaches. The head of the train pushes the air in the train-running direction to move forward in the tunnel, while the air enters neighboring track 2 and some part of the air flows into the ventilation shaft 1. The ventilation and aerodynamic characteristics in the tunnel including train-induced airflow are investigated by predicting the mass flow rate in the tunnel ventilation systems. Figure 4 shows the mass flow rates of the supplied, discharged air through all shafts and remained air. The positive mass flow indicates the supplied air, i.e., the air enters into the tunnel and the negative mass flow shows the discharged-air from the tunnel. The mass flow rate of the airflow at the exits of the shafts depends on the train movement such as acceleration, constant speed, deceleration and passing by the shafts. The remained pollutant air inside the tunnel is low due to proper ventilation. The mass flow rates at the exits of various shafts when the train runs in the track 2 are shown in Fig. 5. There are similar airflow behaviors when the train runs in the track 2 except at the natural shaft. The discharged air through the natural shaft is high due to the piston-effect.

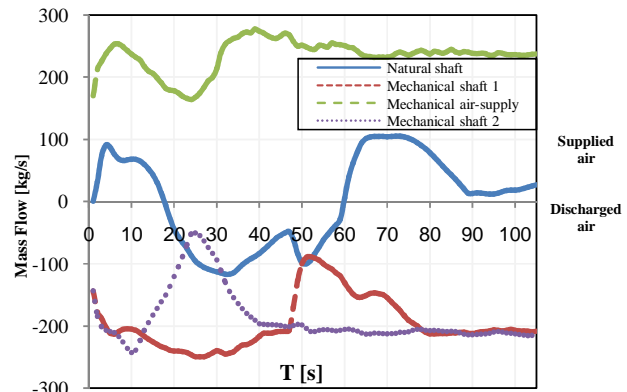


Fig. 5 Mass flow rates at the exits of the shafts when the train runs in the track 2

C. Effect of the two trains running in opposite direction of the twin-track tunnel on the ventilation performance

The movement of the two trains in the subway tunnels generates large airflows with periodical variations in airflow velocity and pressure. The air is supplied mostly through the mechanical air-supply and the rest of the air enters through the natural shaft. The air pollutants distributed by moving trains are transported and diffused with the airflow inside the tunnel.

Figure 6 shows the mass flow rates of the supplied, the discharged and the remained air. The supplied-air does not reach the natural shaft due to the induced and circulating airflow inside the tunnel. The discharged-air is less than the supplied-air while the train accelerates and runs at constant speed. The mass flow rate at the mechanical ventilation shafts has differences due to acceleration of the train and the location of the mechanical air-supply. Figure 7 shows the airflow velocity contour at the track 1 before the trains pass. The airflow velocity at the station A decreases when the train has constant speed and the airflow velocity at the station B is high due to the induced airflow when train approaches the station B. Main problem in the twin-track tunnel is the fast passing of the trains, where significant aerodynamics forces can cause aural discomfort to passengers and potentially affect safe operation. The pollutant air in the tunnel is high when two trains run at the same time. The average velocity of the airflow behind the train increases as the train accelerates and it decreases rapidly as the train runs with constant speed in the station A. The velocity increases at the station A again after the train decelerates due to the piston-effect. The airflow velocity in the station B is similar as the station A. The natural shaft is the closest shaft to the station A. The fresh air enters into the tunnel through the natural shaft instead of the pulling the airflow inside the tunnel.

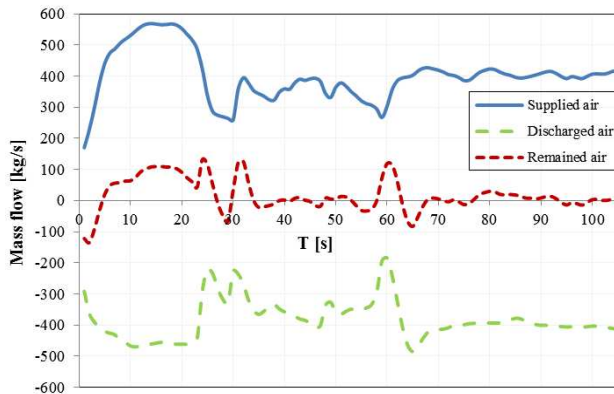


Fig. 6 The airflow balance when two trains run simultaneously in the twin-track

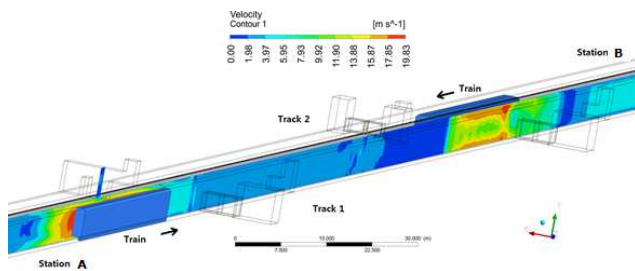


Fig. 7 Velocity contour plot at the track 1 before the trains cross

IV. CONCLUSIONS

The subway environment is investigated for the IAQ by analyzing the ventilation systems. The subway has various IAQ factors such as station structure, ventilation, air pollutions, and etc. The ventilation performance of the subway twin-track tunnel is observed in this research. The existing subway tunnel is modeled and investigated to analyze the ventilation performance. The computational analysis of the twin-track tunnel is performed by solving Reynolds-averaged Navier-Stokes equations for the train-induced unsteady airflow. The airflow inside the twin-track tunnel is computed by using ANSYS CFX software. The tunnel ventilation is observed when one train runs and when two trains run at the same time in the twin-track tunnel. And also the twin-track tunnel is analyzed when all shafts function as the natural ventilation shafts to show the influence of the piston-effect on the tunnel ventilation. The supplied air pushes the pollutant air in the tunnel. The pollutant air is discharged by the mechanical ventilation shafts. The supplied air and the discharged air are balanced when one train runs in the twin-track tunnel. The pollutant air in the tunnel is higher when two trains run. The remained pollutant air inside the tunnel moves toward the stations. The station A needs the improvement studies as the train accelerates.

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