Numerical Simulation in the Air-Curtain Installed Subway Tunnel for the Indoor Air Quality

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

***Abstract*—**The Platform Screen Doors improve Indoor Air Quality (IAQ) in the subway station; however, and the air quality is degraded in the subway tunnel. CO_2 concentration and indoor particulate matter value are high in the tunnel. The IAQ level in subway tunnel degrades by increasing the train movements. Air-curtain installation reduces dusts, particles and moving toxic smokes and permits traffic by generating virtual wall. The ventilation systems of the subway tunnel need improvements to have better air-quality. Numerical analyses might be effective tools analyze the flowfield inside the air-curtain installed subway tunnel. The ANSYS CFX software is used for steady computations of the airflow inside the tunnel. The single-track subway tunnel has the natural shaft, the mechanical shaft, and the PSDs installed stations. The height and width of the tunnel are 6.0 m and 4.0 m respectively. The tunnel is 400 m long and the air-curtain is installed at the top of the tunnel. The thickness and the width of the air-curtain are 0.08 m and 4 m respectively. The velocity of the air-curtain changes between 20 - 30 m/s. Three cases are analyzed depending on the installing location of the air-curtain. The discharged-air through the natural shafts increases as the velocity of the air-curtain increases when the air-curtain is installed between the mechanical and the natural shafts. The pollutant-air is exhausted by the mechanical and the natural shafts and remained air is pushed toward tunnel end. The discharged-air through the natural shaft is low when the air-curtain installed before the natural shaft. The mass flow rate decreases in the tunnel after the mechanical shaft as the air-curtain velocity increases. The computational results of the air-curtain installed tunnel become basis for the optimum design study. The air-curtain installing location is chosen between the mechanical and the natural shafts. The velocity of the air-curtain is fixed as 25 m/s. The thickness and the blowing angles of the air-curtain are the design variables for the optimum design study. The object function of the design optimization is maximizing the discharged air through the natural shaft.

***Keywords*—**air-curtain, indoor air quality, single-track subway tunnel

I. INTRODUCTION

SUBWAY occupies most of public transportation in the major cities. Subway environment requires efficient ventilation systems.

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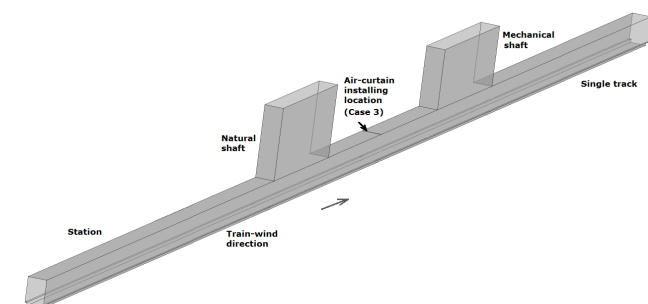
An installation of Platform Screen Doors (PSDs) in the stations improves the ventilation systems and air-conditioning. The PSDs reduce noise and wind blasts caused by a train and improve safety and comfort within the platform environment [1]. The subway tunnel has much higher CO_2 concentration and indoor particulate matter value than the platform. The PSDs degrade the air quality in tunnels while reducing ventilation by the train-induced airflow. Proper ventilation is needed to maintain good Indoor Air Quality (IAQ) in subway 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 concentration than the platform [2]. Air-curtains are installed at the doorways of buildings and enclosures to improve ventilation systems. Air-curtain installation saves energy in public buildings and reduces chemical species, dusts and radioactive particles [3]. The fine dust which makes the IAQ worse is frequently transported into platform by subway trains [4]. In underground tunnels, air-curtain reduces the moving toxic smokes and permits traffic and transportation. Air-curtains are mainly used on emergency situations such as fire conditions [5]. The purpose of this research is to understand the flowfield inside the air-curtain installed single-track subway tunnel. The subway tunnel is simulated and analyzed by using ANSYS CFX software [6]. Numerical results help to find the optimum ventilation systems for the subway tunnel to protect the subway environment.
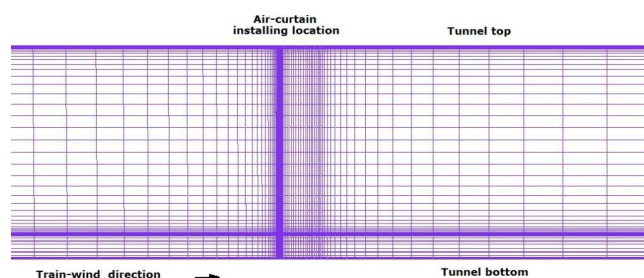
II. NUMERICAL ANALYSIS

A. The computational domain and grid of the single-track subway tunnel

The single-track subway tunnel is assumed to be straight. The computational domain of the subway tunnel is fluid domain. The domain is computed without the train runs. The computational domain of the single-track subway tunnel is shown in Fig. 1 a). The tunnel has single track, the natural shaft and the mechanical shaft. The tunnel is 400 m long, 6.0 m high and 4.0 m wide. The PSDs installed station is 120 m long. The natural shaft is installed at 50 m from the station while the mechanical shaft is 120 m from the station. The air-curtain is installed at the top of the subway tunnel. The thickness and the length of the air-curtain are 80 mm and 4.0 m respectively. The design of air-curtain depends on the installation site and on the size of the opening [7]. There are some zones of the air-jet of the air-curtain depending on the height of the air-curtain installing location and the velocity of the air-curtain. They are the

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potential core, the transition, the developed and the impinging zones.

a) The single-track subway tunnel without the train

b) Generated grid around the air-curtain (side view)
Fig. 1 The computational domain and grid

The computational grid is generated by structured grid. Dense grid is distributed around the wall of the tunnel and around the air-curtain as shown in Fig.1 b). 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. 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 0.001 - 0.5 m in Z direction. In the cross-section of the tunnel, the grid size is between 0.001 m - 0.05 m in X and Y directions.

B. Analysis: The computational tools and Turbulence model

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. 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-ω 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 [8]. 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 (Cluster system: Core 2 Quad 2) running Linux operating system.

C. Boundary and simulation conditions of the computational domain

The working fluid of the domain is an air at the 25℃ of temperature under atmospheric pressure condition. Adiabatic wall boundary condition is used for the tunnel body as shown in Table 1. All walls are treated as viscous adiabatic surfaces with a no-slip velocity condition. Opening conditions are at the natural-shaft and at the ends of the tunnel. Mass flow rate is 64.5 kg/s at the mechanical shaft as outlet boundary condition. The air-curtain velocity changes between 20~30 m/s. The flowfield is analyzed by steady state without the train runs. The velocity of the train-wind in the tunnel station is 4 m/s.

TABLE I
BOUNDARY CONDITIONS OF THE SUBWAY SINGLE-TRACK TUNNEL

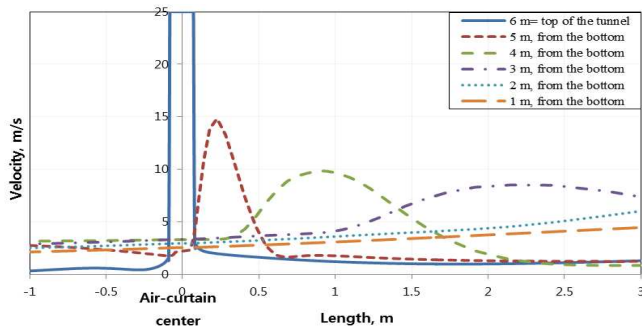| Boundary condition	Location	Value
Inlet	Air-curtain, Tunnel end (Station)	20, 25, 30 m/s
Outlet	Mechanical shaft	4 m/s
Opening	tunnel end, Natural shaft exit,	64.5 kg/s
Wall	tunnel body,	0 Pa

III. RESULTS AND DISCUSSION

A. The installing location of the air-curtain in the single-track subway tunnel

The IAQ level in the subway tunnel degrades by increasing the frequency of the train operation and the number of the train. The air pollutants and fine dusts in the subway tunnel are frequently transported into the station and the train. Air-curtains reduce the moving toxic smokes, dusts and provide a dynamic barrier in the subway tunnel. The tunnel requires more ventilation systems to keep the air quality clean. The pollutant-air is pushed toward the stations by the train-wind. Dispersion of gaseous pollutants is dominated by the train-induced airflow in the tunnel. The pollutants are transported along with the airflow 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 the train lifts fine particles. Air-curtain installation saves energy in public buildings and reduces chemical species, dusts and radioactive particles [3]. Air-curtains are installed at the doorways of buildings and enclosures to reduce air transfer across air curtains. This study helps to find proper air-curtain and the installing location of the air-curtain in the existing tunnel.
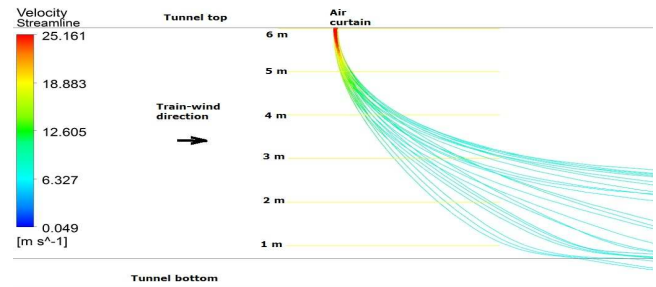
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TABLE II
THE LOCATIONS OF THE AIR-CURTAIN FROM THE NATURAL SHAFT

Case 1	35 m from the Station (15 m before the Natural shaft)
Case 2	15 m after the Natural shaft
Case 3	30 m after the Natural shaft

Table 2 shows three cases depending on the installing location of the air-curtain in the tunnel. The air-curtain is installed at the top of the tunnel 15 m before the natural shaft in Case 1. The air-curtain is installed at the top of the tunnel between the natural and mechanical shafts in other cases. The air-curtain is at 15 m after the natural shaft in Case 2 while at 30 m after the natural shaft in Case 3. The designed air-curtain dimensions for load are chosen as the thickness and width of the air-curtain are 0.08 m and 4.0 m. The velocity of the air-curtain changes between 20 ~ 30 m/s. The design of air-curtain depends on the installation site and on the size of the opening [7]. There are zones of the air-jet of the air-curtain depending on the height of the air-curtain installed area and the velocity of the air-curtain. The air-curtain effect is computed with the train-wind velocity of 4 m/s at the tunnel station. The subway tunnel is computed without the air-curtain to compare the efficiency of the air-curtain. Figure 2 shows the centerline velocity distributions of the air-curtain from the top to the bottom of the tunnel when the air-curtain and the train-wind velocities are 20 m/s and 4 m/s, respectively in Case 1. The potential core of the air-curtain is around the 5.3 m from the bottom. There are the transition, and the impinging zones around 4.3 m and 0.3 m from the bottom of the tunnel, respectively. The injected-air from the air-curtain cannot reach the bottom of the tunnel when the train-wind velocity, wake flow behind the train is 4m/s.

a) Air-curtain velocity at the center of the tunnel in 1- 6 m from the bottom of the tunnel

b) Velocity streamline of the air-curtain and heights of the tunnel
Fig. 2 The velocity distribution of the air-curtain of Case 3

B. The air-curtain influence at the natural shaft and at the tunnel after the mechanical shaft

The single-track subway tunnel is computed without the air-curtain to investigate the effect of the air-curtain to the discharged-air through the natural shaft and at the tunnel after the mechanical shaft. The tunnel aerodynamics deals with the performance of the ventilation systems and a train-wind inside the tunnel. The induced airflow 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 humidity and IAQ. The air exchange implies the demand of the ventilation for the tunnel pollutant-air. The ventilation system in the subway has an important function to discharge pollutant-air from the tunnel. The pollutant-air is discharged through the natural and the mechanical shafts. The mass flow rate through the mechanical shaft is about 64.5 kg/s. The pollutant-air inside the tunnel is discharged using axial flow fans of the mechanical shaft. Table 3 and 4 show the mass flow rate at the natural shaft and after the mechanical shaft, while the train-wind and the air-curtain velocity is 4 m/s respectively. Positive mass flow shows the fresh-air enters into the tunnel, while negative mass flow shows the discharged-air. The fresh-air enters into the tunnel through the natural shaft instead of pulling the airflow inside the tunnel. The mass flow rate after the mechanical shaft is high is shown in Table 4. Figure 3 shows the velocity distributions at the tunnel with and without the air-curtain of Case 3. The natural shaft discharges the airflow due to the train-induced airflow. The discharged-air through the natural shaft increases when the air-curtain is installed in the tunnel.

TABLE III
MASS FLOW OF THE NATURAL SHAFTS WHEN THE VELOCITY AND LOCATIONS OF THE AIR-CURTAIN ARE CHANGED AND THE TRAIN-WIND VELOCITY IS 4 M/S

Mass flow, (kg/s)	Air-curtain velocity, (m/s)			
	0	20	25	30
Case 1	8.66508	-4.15521	-4.10521	1.14103
Case 2		-26.4825	-32.0419	-33.8802
Case 3		-31.5225	-35.0709	-38.6931

※ Negative implies the discharged air from the tunnel.

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TABLE IV
MASS FLOW OF THE TUNNEL AFTER THE MECHANICAL SHAFT WHEN THE
VELOCITY AND LOCATIONS OF THE AIR-CURTAIN ARE CHANGED AND THE
TRAIN-WIND VELOCITY IS 4 M/S

Mass flow, (kg/s)	Air-curtain velocity, (m/s)			
	0	20	25	30
Case 1	-55.676	-50.0302	-51.9663	-59.1001
Case 2		-27.7085	-24.0449	-24.1022
Case 3		-22.2649	-20.5122	-18.68632

The mass flow rate at the exit of the natural shaft and the tunnel after the mechanical shaft are given in Tables 3 and 4. The discharged-air through the natural shafts increases as the velocity of the air-curtain increases. The discharged-air is lower in Case 1 than other cases. The mass flow rate in Case 3 is higher than that in Case 2. The jet-air from the air-curtain cannot reach the bottom of the tunnel due to the train-wind. The mass flow rate decreases in the tunnel after the mechanical shaft as the air-curtain velocity increases as shown in Table 4. The pollutant-air moves toward the tunnel and enters into the station platform area as PSDs open. The stations need the air quality improving tools such as electrostatic precipitators, air-curtain, a barrier, and etc. [9], [10].

a) Velocity of the air-curtain is 0 m/s
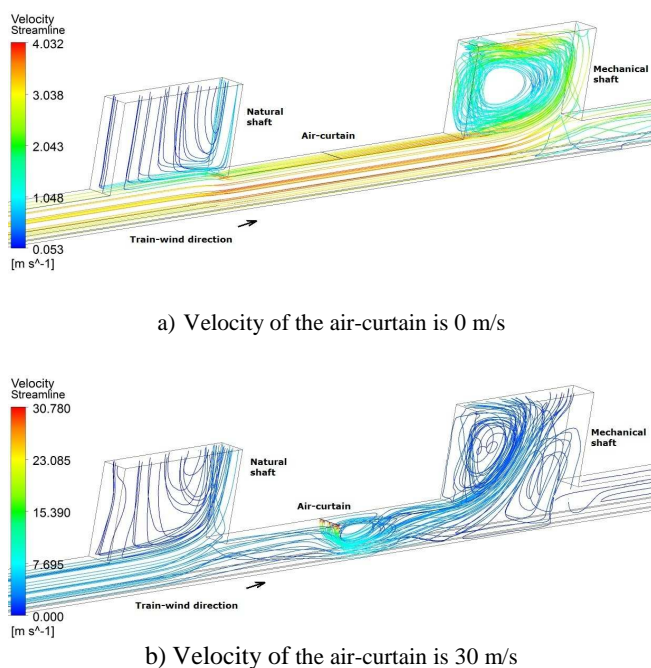

b) Velocity of the air-curtain is 30 m/s

Fig. 3 Velocity streamline in the tunnel when the velocity of the train-wind is 4 m/s

C. Proper dimensions and installing location of the air-curtain in the single-track subway tunnel

The computational study of the air-curtain installed subway tunnel provides important results for the optimum design study. The design parameters for the air-curtain design are the thickness of the air-curtain, the height of the tunnel, static pressure difference around the air-curtain such as the upstream and the downstream static pressures, the train-wind velocity rate in the tunnel, and the blowing angle of the air-curtain. Dimensions of the air-curtain designed for the road tunnel are used in this study. The velocity and the thickness of the air-curtain must be higher and thicker for the industrial applications. Figure 4 shows velocity distributions of Case 3 when the air-curtain and the train-wind velocities are 25 m/s and 4 m/s, respectively. The air-curtain covers top part of the tunnel as virtual wall. The velocity of the air-jet from the air-curtain is important variable to cover the cross-section of the tunnel. The thickness and the blowing angle of the air-curtain will be the design variables for the optimum design study. The location for the air-curtain installation is chosen as the location of Case 3 [11]. The velocity of the air-curtain is fixed at 25 m/s. The object function of the optimization is maximizing the discharged air through the natural shaft.
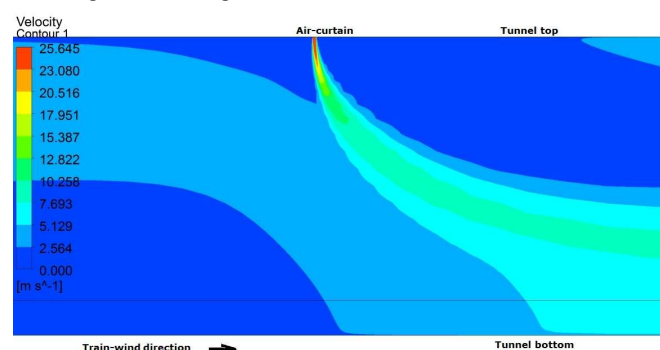

Fig. 4 Velocity contour at the center of the tunnel when the air-curtain and the train-wind velocities are 25 m/s and 4 m/s (Case 3, side view)

IV. CONCLUSIONS

The air-curtain installed single-track subway tunnel is investigated for the IAQ by analyzing the airflow behaviors inside the tunnel. The ventilation systems of the subway tunnel need improvements to have better air-quality. Numerical analyses are required to understand the air-curtain installed subway tunnel and to improve the ventilation performance of the tunnel. The analysis of the subway tunnel is performed by solving Reynolds-averaged Navier-Stokes equations. The airflow inside the single-track subway tunnel is computed by using ANSYS CFX software. The tunnel has the natural shaft, the mechanical shaft, single-track and the PSDs installed station. The height, width and length of the tunnel are 6 m, 4 m and 400 m while the thickness and width of the air-curtain are 0.08m and 4m. The air-curtain is installed at the top of the tunnel. Three cases are analyzed depending on the installing location of the air-curtain. The air-curtain velocities are 20, 25 and 30 m/s. The pollutant-air is exhausted by the mechanical and the natural shafts. The discharged-air through the natural shafts increases as the velocity of the air-curtain increases in Cases 2 and 3. The discharged air is lower in Case 1 than in other cases. The mass flow rate in Case 3 is higher than those of other cases. The mass flow rate decreases after the mechanical shaft as the velocity of the air-curtain increases. The thickness and the blowing angle of the air-curtain become the design variables for the optimum

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design study. The installing location of the air-curtain is chosen as the location of Case 3. The velocity of the air-curtain is fixed at 25 m/s. The object function of the optimization study is maximizing the discharged-air through the natural shaft.

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