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RESEARCH ARTICLE

Air Conditioning System Design to Reduce Condensation in an Underground Utility Tunnel Using CFD

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ABSTRACT In this study, the internal environment such as the air temperature, humidity, and wall temperature of the underground utility tunnel, was analyzed. The current status and problems of the air conditioning system were examined by analyzing the capacity of the exhaust fan and the air velocity inside the utility tunnel. The field experiment showed that the utility tunnel has a relative humidity of 95% or higher for most sections during summer. The deviation of the internal air temperature was about 4 °C depending on the section, and the dew condensation occurred. However, most of the exhaust fans has a capacity below the standard minimum air velocity of $2.5 m\cdot s^{-1}$. In particular, in the section where dew condensation occurred, the air velocity was 0.26 to $0.97\ m\cdot s^{-1}$, indicating the presence of stagnant air inside the facility. Therefore, this study attempted to minimize dew condensation by calculating the proper exhaust fan capacity using computational fluid dynamics and installing circulation fans and duct systems in the section where the dew condensation occurred. As a result, when a circulation fan was installed, it was possible to increase the air velocity inside the utility tunnel, and the relative humidity could be reduced by about 78%. By installing a duct, the direct supply of external air or the discharge of internal humid air was simulated for the section where dew condensation occurred. The result showed that the relative humidity could be reduced by about 78% when the duct system was operated in the intake direction.

INDEX TERMS Condensation, CFD, circulation fan, duct, ventilation, underground utility tunnel.

I. INTRODUCTION

A. THE CONCEPT AND CURRENT STATUS OF THE UNDERGROUND UTILITY TUNNEL

An underground utility tunnel is a structure that accommodates and supplies two or more types of urban lifelines such as pipelines for electricity, gas, water supply, telecommunication, and sewage. In addition, it is a facility installed underground to improve the aesthetics, preservation of road structures, and smooth flow of traffic, especially in urban areas [1]. If a single pipeline for each electricity, gas, and water is constructed in underground, the increased cost due to construction work and the formation of a complex underground structure network can cause problems in the usability

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of underground space. In addition, the repeated excavation and revised drawing information are omitted for maintenance work may lead to the destruction of a single pipeline buried during construction in the area later. Therefore, the advantages of reducing costs (e.g. installation and accidental) can be expected by burying and managing each of the dispersed pipelines [2]. In South Korea, specifically in Yeouido Common District, which was planned and constructed at the time of Yeouido development in 1969, utility tunnels were constructed in parallel with subway lines in Seoul and Busan in the 1970s. In the 1980s and 1990s, utility tunnels were constructed according to the public development plan when developing new towns. Since the 2000s, the utility tunnel has been introduced to build social infrastructure around new towns. Today, about 38 utility tunnels (98 other) are in operation nationwide [3].

B. DESIGN CRITERIA AND LIMITATIONS OF THE VENTILATION SYSTEM OF THE UNDERGORUND UTILITY TUNNEL

In the past, the Korean standards for the utility tunnel air conditioning system were established as subsidiary facilities and not as separate facilities for the air conditioning system. The design standards for the air conditioning system of the utility tunnel proposed by the Ministry of Construction and Transportation in 2004 mentioned that 'An auxiliary facilities, lighting, ventilation, and drainage facilities should be sufficiently supported in the event of an earthquake in the installation location' [4]. These facilities are designed to be safe against seismic loads caused by inertial forces by adding fixed loads during earthquakes. Therefore, the design standards for the air conditioning system of the utility tunnel have been established from the perspective of seismic design and structural design rather than factors to be considered during actual installation such as the location, spacing, and capacity of the ventilation fan. The standards revised in 2006 suggested design standards for air velocity in the utility tunnel, the flow velocity of the ground vent, air intake and vertical exhaust duct. However, does not directly present the standard specification for air conditioning system capacity, and location selection. Therefore, most of the air conditioning systems of utility tunnels constructed in the past lack an engineering design basis, and were designed based on the experience of the constructors. Since then, the standards for the installation of the utility tunnel have been established by the Ministry of Land, Transport and Maritime Affairs in 2010, and the parts corresponding to the general matters of the existing utility tunnel design standards have been revised. The design items for the air conditioning system include air flow velocity in the utility tunnel, the flow velocity of the ground vent, the ventilation fan design standard, the required ventilation time, the air temperature in the utility tunnel, and the installation standard of the vertical ventilation duct. However, the design criteria for the flow velocity of the ground vent not only have a poor correlation with air velocity but also may not significantly satisfy the number of ventilations (air exchange rate per hour) depending on the size of the utility tunnel. The capacity of the ventilation fan cannot be calculated exclusively from the air velocity in the utility tunnel and the air velocity of the ground vent. It must comprehensively consider the utility tunnel cross-sectional area and internal load. Therefore, it should be used as auxiliary data, and direct standards such as the number of ventilation (air exchange rate per hour) are required. Additionally, the burying depth of the inlet and outlet may be different depending on the construction environment of the utility tunnel, the tunnel section may change or there may be stairs between tunnel sections. Furthermore, it is important to comprehensively calculate the air exchange rate per hour. However, the current design standards of both South Korea and Japan do not take these considerations into account, and as for the design criteria for the time required for ventilation, the basis and quantitative analysis of the criteria for completing ventilation are unclear (Table 1). In the case of utility tunnels in New York, large exhaust fans are installed for smoke control in case of fire as well as for internal ventilation. Whereas in the case of domestic utility tunnels, ventilation facilities for smoke control are not considered. Therefore, the unavailability of smoke controls may restrict response during fire disasters. Although it is difficult to expect sufficient natural ventilation because the utility tunnel is a structure buried in the ground, the air conditioning system design standards are insufficient. Therefore, it is necessary to study the air conditioning system for revision of the standard that can present sufficient engineering grounds and specific design standards.

C. PROBLEMS WITH AIR ENVIRONMENT AND CONDENSATION IN UNDERGROUND UTILITY TUNNEL

Unlike other structures on the ground, the utility tunnel has difficulty in controlling the internal air environment, such as air temperature and humidity, because there is no sunlight and the exchange of air is insufficient. In addition, if harmful gases are generated and accumulated in the utility tunnel, the risk is very high. If the heat discharged from the power cable is not easily emitted outside, the transmission efficiency of the power cable may be lowered due to the accumulated heat [5]. Also, when groundwater infiltrates or rainwater flows in through vents and entrances, the durability of the facility may be compromised due to the dew condensation in the utility tunnel. In addition, the inflow of fresh air from the outside is insufficient because ventilation with the outside air is generally limited. Therefore, the underground structure is exposed to the various problems, and is particularly exposed to the risk of condensation in the summer when frequent rainfall and high humidity air occurred. Accordingly, a number of previous studies have been carried out to analyze the cause and prevention measures of the condensation inside the facility. In Pereira et al. [6] reviewed the humidity of a building according to the type of cladding and its problems through previous studies and example analysis and identified the causes of humidity problems including condensation. In Ueno [7] analyzed the thermal behavior of basement wall

TABLE 1. Domestic and foreign standards for the air conditioning system of the underground utility tunnel.

Criteria	South Korea [24]	Japan [25]	USA [25]	China [26]
Air velocity in underground utility tunnel	Over 2.5m·s^{-1}	Below 2.0 m·s^{-1}	-	Over 1.33 m·s^{-1}
Air velocity at vertical ventilation duct	Below 5.0 m·s^{-1}	Below 5.0 m·s^{-1}	-	-
Ventilation fan design criteria in case of fire	Operation for more than 60 minutes at 250 °C during fire		Continuous operation even at temperatures above 65 °C	-
Ventilation fan capacity	-		Over 1,750 RPM or over 500 CFM	-
Number of ventilations	-	-	15 times·hr^{-1}	6 times·hr^{-1} (12 times·hr^{-1} in emergencies)
Time required for ventilation	Within 30 minutes	Within 30 minutes	-	-
Air temperature in underground utility tunnel	Below 40 °C	Below 40 °C	-	-
Vertical ventilation duct installation standard	Installed every 250 m	Install natural ventilation duct and forced ventilation duct every 100 m	-	-
Oxygen concentration in underground utility tunnel	-	-	19.5~23.5%	-

insulation through on-site monitoring and simulation, suggesting that the summer condensation problem is caused by the inside and outside temperature difference. Several studies have also been conducted to prevent condensation as well as to analyze the causes of condensation in underground structures.

In Oh [8] and Jeon [9] suggested improvement measures through the construction of wall insulation and anti-condensation materials by analyzing the causes of condensation damage and causes of condensation in domestic houses and underground parking lots, respectively. However, research on the improvement of the already constructed underground structures was insufficient. Meanwhile, studies have also been conducted to analyze the characteristics of the air environment in the utility tunnel and to evaluate the air conditioning system. Other studies related to utility tunnels were focused on exhaust fan design [10], internal air temperature and humidity environment analysis [11], [12], [13], optimization for ventilation and humidity control [14] and numerical simulations of various ventilation systems [15], [16] were performed. In Li et al. [15] distinguished common risks inside tunnels, such as high humidity problems, heat transfer, pollutants, and pest growth. In He [14] and Shahrour et al. [17] classified various types of equipment installed inside utility tunnels into categories to monitor and suppress commonly known problems in utility tunnels. Most of these literatures emphasized the need for smart sensors that could monitor internal environmental conditions such as air temperature, humidity, air quality, smoke, gas emissions, and water inflow. However, most of the previous studies were limited to the analysis of the internal environment of the utility tunnel. They did not consider the analysis of the airflow inside and the air conditioning system installed in the utility tunnel.

Meanwhile, condensation is one of the important issues in utility tunnel [18]. In the case of utility tunnels, the effect of natural ventilation is very small because they are buried underground. Therefore, if the forced ventilation system is not properly designed, the internal air is stagnant, and the high humidity air is likely to stagnate due to the inflow of rainwater or the inflow of high temperature and high humidity outside air. If humid air is continuously formed inside the utility tunnel, it can cause corrosion of metal facilities including various pipes, and a humid environment accelerates the formation of mold and bacteria, which can adversely affect the health of workers. In addition, in the case of power lines and telecommunication lines, improper temperature and humidity can cause electric sparks and ignite combustibles [19], [20], [21], [22]. Air conditioners and dehumidifiers are generally used to remove high humidity in general buildings. Air conditioners and dehumidifiers use the compression and refrigeration cycle of water vapor to lower the humidity in the air. That is, water vapor is liquefied by lowering the temperature of the air to the dew point. However, during this process, unnecessary energy consumed during supercooling and reheating of the process air is generated, and energy efficiency may be lowered [23]. In addition, the utility tunnel is several kilometers long and includes several natural ventilation openings. This decreases the dehumidification efficiency using the device and requires energy consumption. On the other hand, natural ventilation is one of the most basic methods for improving air quality in utility tunnels [2]. Therefore,

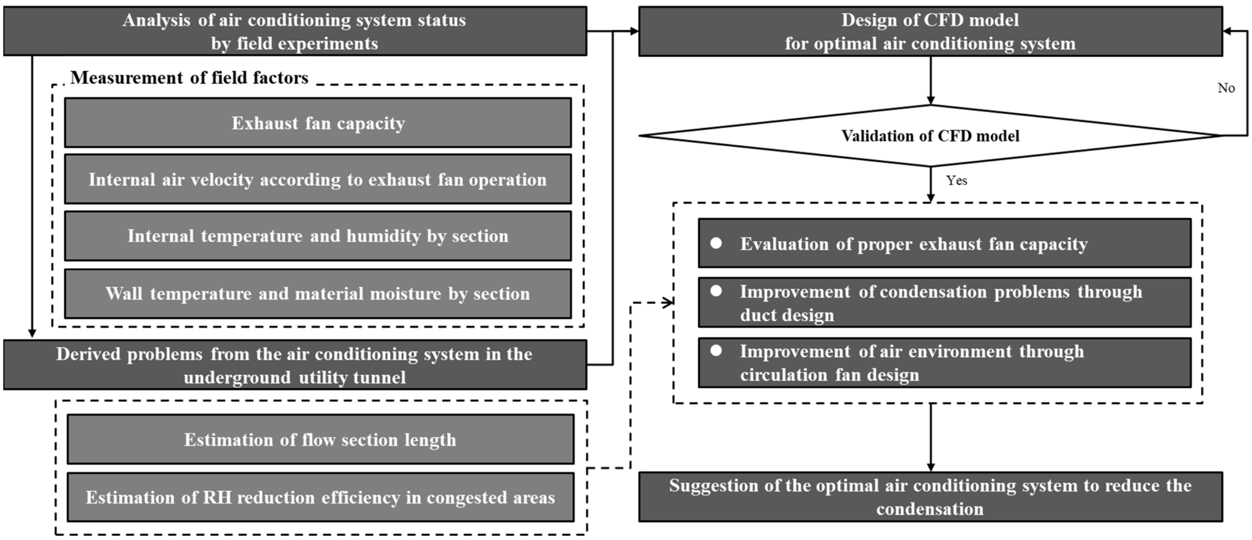

FIGURE 1. Flowchart of the experimental procedure.

in the case of utility tunnel, the removal of humidity through natural ventilation should be considered first.

D. OBJECTIVES OF THE STUDY

In this study, the air conditioning system installed in the target utility tunnel located in Cheongju-si was evaluated and the internal air flow was examined. In addition, the internal environment of each section of the utility tunnel was analyzed by measuring the internal air temperature, humidity, and wall temperature. Through the above analysis, the aerodynamic problem of the dew condensation of the target utility tunnel was identified, and the improvement plan of the air conditioning system was studied using computational fluid dynamics (CFD). First, the proper exhaust fan capacity was calculated using CFD to solve the aerodynamic problems studied through field experiments. In addition, the installation of auxiliary air conditioning equipments such as circulation fans and ducts were simulated to solve the problem of air stagnated and condensation in the target utility tunnel by the CFD model. From this, the amount of relative humidity reduction over time was calculated, and the flow velocity for each section inside the utility tunnel was evaluated due to the operation of the auxiliary equipment. Finally, the local air exchange rate was improved for the stagnant section where the humidity was very high.

II. MATERIALS AND METHODS

Fig. 1 shows the research flow chart of this study. First, field experiments were conducted to analyze the current status and problems of the target utility tunnel. In order to determine the appropriate capacity of the installed air conditioning system, the exhaust fan flow rate and the internal flow velocity for each location in the utility tunnel were measured. In addition, the internal air temperature, humidity, wall temperature, and material moisture were measured and analyzed to identify the cause of dew condensation, which was a major problem of the target utility tunnel. The results of the field experiments were used not only to evaluate the air conditioning system of the target utility tunnel, but also to identify the problems of the target utility tunnel and the section where the improvement of air conditioning system was required. Additionally, the results of the field experiment were also used to validate the CFD model. As a result, the stagnated section of the target utility tunnel and the section vulnerable to condensation were identified, and a CFD model was designed for the optimal air conditioning system design for reducing the occurrence of condensation. The CFD model was designed for the summer season when the humidity of the air was high, and the section where dew condensation occurred frequently was selected as the target model. The boundary conditions of the CFD model were designed following the actual data from the field experiment. The CFD model was validated for internal flow formation according to the operation of the exhaust fan, and the improvement of the air conditioning system of the target utility tunnel was analyzed using the validated CFD model. First, the measured exhaust fan capacity was compared with the domestic and foreign standards for utility tunnel air conditioning systems, and the proper fan capacity was suggested through CFD simulation results. Next, the duct system was studied to remove humid air in the section where dew condensation occurred. The relative humidity removal efficiency in the section was evaluated according to the intake and exhaust of the duct system. In addition, the improvement of the air flow inside the utility tunnel and the relative humidity removal efficiency for the section where dew condensation occurred were analyzed according to the number of circulation fans, the installation location, and the direction of circulation fans (intake or exhaust). Finally, an optimal air conditioning system for reducing dew condensation was suggested.

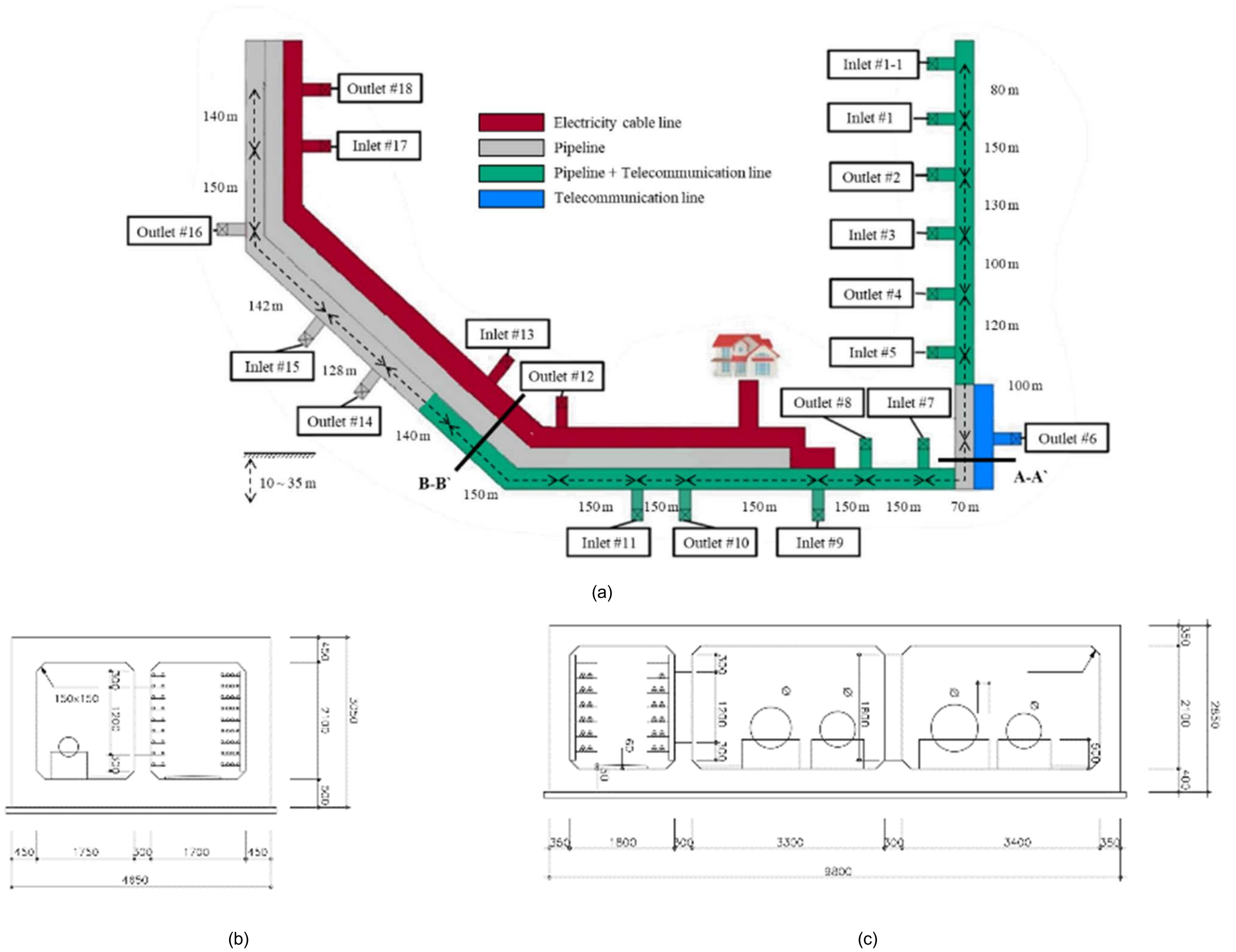

FIGURE 2. Schematic diagram and cross-section of target underground utility tunnel: (a) Top view of diagram containing the length of tunnel section and location of each vertical ventilation duct (b) Cross-section of A-A′ (c) Cross-section of B-B′.

A. TARGET UNDERGROUND UTILITY TUNNEL

The target underground utility tunnel is located in Cheongju-si, Chungcheongbuk-do which was constructed in December 2001 and is buried from 10 m to 35m underground. The total length of the tunnel is 2,426 m which accommodates pipelines for water supply (2,426 m), electricity (1,426 m), and telecommunication (1,734 m) (Fig. 2).

A total of 10 vertical exhaust ducts and 8 inlet vertical ducts are installed alternately, and a negative pressure ventilation is performed using the exhaust fan. The mechanical ventilation operates the exhaust fan of the vertical exhaust duct to discharge the internal air to the outside and then introduces the outside air from the inlet vertical duct.

The manual control system that operates the exhaust fan based on the experience of the administrator and the automatic control method by the Remote Terminal Unit (RTU) temperature and humidity sensor installed near each exhaust fan. In the automatic control system, the exhaust fan operates when the internal air temperature near the exhaust fan is more than 25 °C or is more than 80% relative humidity. The exhaust fan installed in the utility tunnel was installed during the construction in 2001 and has no history of replacement, thus, there are concerns about the deterioration in terms of efficiency of the equipment. In addition, there is no external temperature and humidity sensor in the target tunnel, and this cannot be considered in the automatic control of the exhaust fan.

Therefore, in the case of hot and humid summer, even when the exhaust fan is automatically controlled based on the internal air temperature and humidity of the utility tunnel, outside air with a higher temperature and humidity often flows in, and the internal high temperature and humidity environment deteriorates, making it difficult to operate. In addition, in most cases, a manual control based on the manager's experience has been used rather than automatic control. And since there are a total of 10 different managers who work in rotation, the consistency and continuity of air conditioning system operation are poor. During the summer season, dew condensation uncontrollably occurred in some sections of the utility tunnel. Dew condensation is a phenomenon in which air with high humidity meets a cold surface and reaches the dew point temperature and dew condensation occurs. In simple terms, there is a temperature difference for each section during summer in the target utility tunnel, which means that a stagnated section may have been formed without sufficient airflow for all sections through the air conditioning system. Therefore, it is necessary to analyze the installed air conditioning system and improve the air environment in the target utility tunnel.

B. COMPUTATIONAL FLUID DYNAMICS (CFD)

Computational Fluid Dynamics (CFD) is a numerical analysis tool that can analyze fluid flow, heat transfer, and chemical action through computer simulation. CFD uses the Navier-stoke equation, a nonlinear differential equation, as the governing equation, and is a tool for simulating numerical analysis using the finite difference method. It is actively used in various fields including machinery, aviation, chemical engineering, manufacturing, civil engineering and construction, and the environment. Recently, many researches are conducted in the agricultural field such as livestock facilities and greenhouse environment analysis [27], [28], [29], [30], [31]. In this study, a three-dimensional grid was designed using a commercial program for CFD (ver. 18.2, ANSYSInc, PA, USA) using the finite volume method to analyze the air conditioning system for reducing dew condensation. This was a set of equations that utilizes the Navier-stokes equations as the governing equations and controls mass, momentum and energy conservation as follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla P + \nabla \tau + \rho \vec{g} + \vec{F} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\vec{v}(\rho h + P)) = \nabla \left(k_{eff} \nabla T - \sum\nolimits_j h_j \vec{J}_j + (\bar{\tau} \vec{v})\right) + S_h \tag{3}$$

where, ρ is the density of the fluid (kg·m^{-3}), $\vec{v}$ is the flow velocity of the fluid (m·s^{-1}), P is the static pressure (Pa), $\vec{\tau}$ is the stress tensor (Pa), and $\vec{g}$ is the acceleration due to gravity. (m·s^{-2}), $\vec{F}$ is the external force (N·m^{-3}), S_m is the mass source term of the mass (kg·m^{-3}), k_{eff} is the effective conductivity (kg·m^{-2}·s^{-1}), T is the temperature (K), E is the specific enthalpy indicating the enthalpy per unit mass (J·kg^{-1}), t is the time (s), $\vec{J}_i$ is the diffusion flux of i type (kg·m^{-1}·s^{-1}), S_h is the enthalpy rise based on the chemical reaction or radiation (kg·m^{-1}·s^{-3}).

C. EXPERIMENTAL PROCEDURE

1) FIELD EXPERIMENT

In the target utility tunnel, a dew condensation between inlet vertical ducts 6 and 8 occurred. So, the capacities of vertical exhaust ducts no. 6 and no. 8 were measured to understand

FIGURE 3. Insufficient space in the external part of the inlet vertical duct for fan capacity measurement.

FIGURE 4. Flow velocity measurement experiment at the inlet of exhaust fan (○: measurement point).

the current status of the air conditioning system and to analyze the problems occurring inside the target utility tunnel. If the airflow station is installed at the external part of the inlet vertical duct to measure the volumetric airflow rate, the distance is less than 50cm from the side wall. It was found that the measured exhaust fan capacity through the airflow station was insufficient (Fig. 3). Therefore, in consideration of the field conditions, the 1-minute average flow velocity was measured at the inlet section of the exhaust fan using a hot wire wind speed sensor (Testo 480, Testo SE&Co. KGaA, Germany), and the air velocity of multiple points were measured for the inlet section of the exhaust fan (Fig. 4). When the exhaust fan was in operation, the air drawn in from the adjacent inlet vertical duct was discharged to the outside through the vertical exhaust duct. However, the inlet vertical duct can be affected by the exhaust fan adjacent to both sides. Therefore, an exhaust fan flow rate was measured under two operating conditions. First, only the target exhaust fan was operated. Second, the target exhaust fan and adjacent fans were simultaneously operated to consider the additional load from the surrounding exhaust fans.

On the other hand, the vertical exhaust and intake duct of the target utility tunnel are alternately installed at intervals of 100 to 150 m. The cross-section of the target utility tunnel changes depending on the location, and there are stairs in some locations. Therefore, it was possible to show a

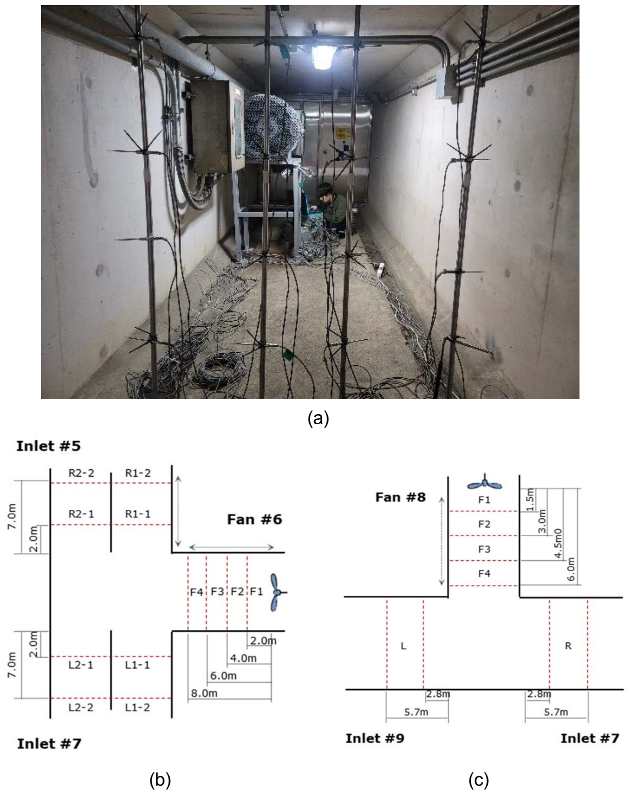

FIGURE 5. Experiment of measuring the airflow at the inner section of the underground utility tunnel when the exhaust fan no 6. or no 8 was operated: (a) Measuring point locations of the airflow sensor installation (b) Section locations of measuring the airflow according to the exhaust fan no. 6 (c) Section locations of measuring the airflow according to the exhaust fan no. 8.

difference in the airflow formed in the utility tunnel according to the operation of the exhaust fan provided in each section, and it was possible to form a stagnated area. So, to analyze this quantitatively, the flow velocity was measured in the corridors near the vertical exhaust ducts no. 6 and no. 8 when the exhaust fan was operating. Since the utility tunnel is a tunnel-type structure with a certain cross-section, the air flow inside the tunnel can be affected by wall friction. So the flow velocity was measured at 9 points on the tunnel cross-section so that the points adjacent to the wall surface and the center point of the cross-section were included and the surface flow velocity was calculated by averaging them. The flow velocity was measured using a Multi-Channel Anemomaster and a heat ray wind speed sensor (Kanomax, USA), and the measurement positions were installed in the vertical exhaust duct corridor where the exhaust fans was installed and, in the corridor where each pipeline was installed (Fig. 5).

On the other hand, dew condensation is a phenomenon that occurs as the water vapor contained in the air is saturated as the relative humidity reaches 100%, and the temperature at which dew condensation occurs is called the dew point temperature. In general, as the temperature decreases, the amount of water vapor that air can contain also decreases. Therefore, dew condensation occurs when the amount of water vapor in the air increases or when the temperature of the air decreases [32]. The wall temperature of the utility tunnel is affected by the underground soil temperature and maintains a constant temperature throughout the year. In particular, in summer, the temperature of the utility tunnel is generally about 10 degrees lower than the outside temperature [33]. Therefore, when high temperature and humid outside air flows into the utility tunnel in summer, the temperature of the air reaches the dew point temperature by contacting the wall of the utility tunnel, which is a relatively low temperature. As a result, dew condensation easily occurs. The target utility tunnel has a dew condensation problem that specifically occurred in some sections during summer. According to the manager of the target utility tunnel, dew condensation problem usually occurred about 30% of the year. Causes of the dew condensation phenomenon include the use of materials with high moisture content, damage and adhesion of the heat insulating material. There are some preparations to prevent dew condensation on underground concrete structures including reinforcement of heat insulating materials, heating using hot air blowers, use of dehumidifiers, improvement of wall finishing materials, and methods of removing high-humidity air by improving ventilation. To improve ventilation, it is necessary to improve the ventilation system installed in the utility tunnel, and the quantitative evaluation of the ventilation system currently installed must be preceded. As a result, it is necessary to evaluate the existence and location of stagnant areas, the capacity of the proper ventilation system, etc., and it is necessary to understand the vulnerable sections of dew condensation by analyzing the air environment data for each section in the utility tunnel. Therefore, the dew point temperature was calculated by measuring the air temperature and humidity of each section of the tunnel, the wall temperature and material moisture content of the target underground tunnel, and the vulnerable section for condensation was identified (Fig. 6). During the experiment conducted on July 20, 2021, and measured outside air temperature was 31.5 °C and the humidity was 61-65%. The target section of the experiment includes exhaust fan no. 6 section where dew condensation occurs habitually, and the section where dew condensation occurs only on a part of the floor. So, the target was the section from the inlet vertical duct no. 5 to the vertical exhaust duct no. 10.

2) DESIGN OF THE CFD SIMULATION MODEL

A CFD model was designed for air conditioning system analysis and improvement proposal presentation for the target utility tunnel (Fig. 7). The target section of the CFD model was selected based on the results of field experiments, where a stagnated section was formed and the currently installed air conditioning system needed improvement. As a result, exhaust fan no. 6 to exhaust fan no. 8 in which stagnated sections were formed before and after the stair section, were selected. Meanwhile, numerical analysis using CFD requires grid network design. Therefore, as the grid becomes dense and the number of grids increases, the computing cost and time required for calculation also increase [28]. Therefore,

FIGURE 6. **Measuring wall temperature and material moisture for each underground utility tunnel section to analyze the cause of dew condensation: (a) Wall temperature measurement using a thermal imaging camera (b) Material moisture measurement of wall using a material moisture meter.**

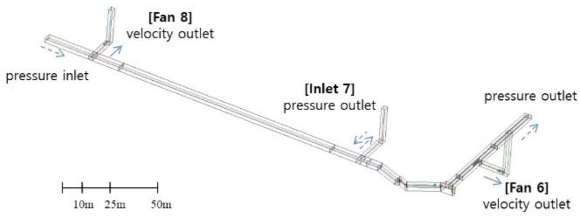

FIGURE 7. **Structural CFD model of target underground utility tunnel and design of inlet and outlet boundary conditions.**

when the size of the analysis space is large or when a large number of complicated shapes were included, the number of grids increases significantly, and the cost and time required for the calculation increase exponentially. The section from exhaust fan no. 6 to exhaust fan no. 8 which is the target section of this research is about 220 m and is composed of a telecommunication pipelines, a drain pipelines, a support base for each pipeline, and a fire hydrant for fire safety, and various equipment. If all such components were reflected in the CFD model, a grid design that reflects the precise shape must be made, which can lead to uneconomical interpretations such as a significant increase in the number of grids. Therefore, it is necessary to simplify the structure shape and disregard tiny shapes does not significantly affect the main airflow in the analysis domain. In this study, structures that do not significantly affect the airflow formed at the inlet and outlet vertical duct of the target utility tunnel were selected to simplify the shape, and grid modeling was performed. The total number of grids was designed to be about 4.2 million.

The boundary conditions at both ends of the central corridor in the target utility tunnel section were defined as Pressure inlet and Pressure outlet, respectively, reflecting the results of field experiments. In the case of the central corridor, since there is no other device to affect the air flow, it was found out that the air flow was formed due to the pressure difference between the nearby inlet and the vertical exhaust duct. As a result of the field experiment, the basic flow from inlet 9 to inlet 7 was formed. Therefore, the boundary condition in the direction of inlet 9 was defined as the boundary condition push inlet, and the boundary condition in the direction of exhaust fan no. 6 was defined as the pressure outlet. In the case of inlet 7, it was defined as a Pressure outlet so that air inflow and outflow would occur. In the case of exhaust fan No. 8, the velocity inlet was defined so that a constant flow velocity was exhausted, and the tunnel wall and the sewage pipe were defined as Wall. In particular, the temperature value measured in the field test was applied to the wall for each section, and the roughness height was 0.001m and the roughness constant was 0.5 in order to consider the wall friction. The result of the field experiment conducted on August 2021 showed that the wall temperature of section 5 ∼ 6 buried relatively deep in the ground was 21.3 °C. The measures value was 1-2 °C lower compared with the wall temperature of other sections. Therefore, the surface temperature of the wall was applied based on the field measurement data.

3) VALIDATION OF THE CFD SIMULATION MODEL

The CFD model designed in this study includes the exhaust fan no. 6, and the internal airflow was greatly affected by exhaust fan no. 6. Therefore, the CFD model was used to validated the air flow formed in the utility tunnel according to the operation of the exhaust fan no. 6. The CFD model validation was performed to quantitatively analyze the air flow velocities in the corridor where the exhaust fan no. 6 was installed and at the central corridor of the utility tunnel (Fig. 5 (b)). For the boundary of exhaust fan no. 6 used in the CFD model, the field measurement values were applied. Since the turbulent flow cannot be accurately simulated as an irregular three-dimensional flow and is not constant in time and space, CFD derives an approximate solution through a turbulent flow model. Presently, various turbulence models have been developed, thus, it is necessary to select an appropriate turbulence model in consideration of the characteristics of the analysis model and environmental conditions. In this study, the Reynolds Averaged Navier-Stokes (RANS) models, which are most often used in the flow analysis of underground structures [26], [34], [35], [36], are used among various turbulence models. The simulation result using Standard k-ε, RNG k-ε, Realizable k-ε, Standard k-ω, SST k-ω were compared.

4) COMPUTATIONAL BOUNDARY CONDITIONS OF CFD SIMULATION MODEL FOR REDUCING CONDENSATION AT TARGET SECTION

In the target utility tunnel, it was found that dew condensation occurred in the section between the vertical exhaust duct 6 and the inlet vertical duct 7 during the rainy season. It is known that the cause of dew condensation in underground structures was that humid air comes into contact with the walls of underground structures at relatively low temperatures and reaches the dew point [37]. Therefore, to reduce the occurrence of dew condensation, it is necessary to remove the humid air by ventilation with the dry air from the outside. In the case of the section where dew condensation occurs

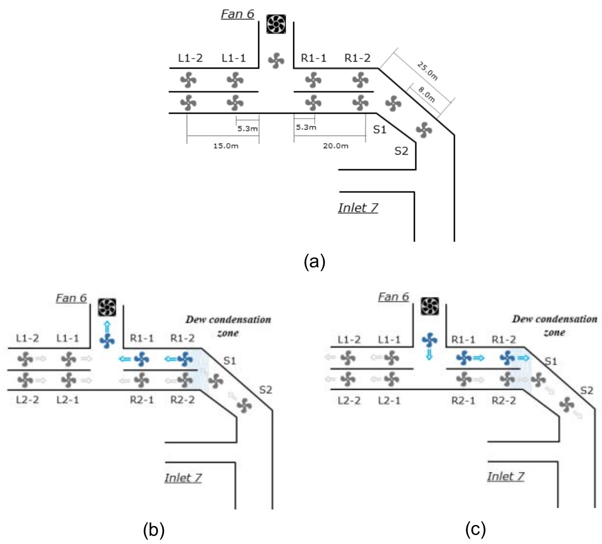

FIGURE 8. **Installation locations of an appropriate circulation fan to solve the section of dew condensation in CFD model: (a) Detailed installation locations of circulation fan(each fan was installed at a height of 0.5 m from the floor) (b) Example of 3 EA installation model of circulation fan for exhaust direction (c) Example of 3 EA installation model of circulation fan for intake direction (Blue fan: installed locations of fan, Grey fan: considered locations of fan in other CFD case) circulation fan.**

in the target utility tunnel, it is found to be a stagnant area that does not replace fresh air from the outside because dew continues to occur despite the operation of the nearby exhaust fan. Therefore, the air conditioning system was designed and evaluated to remove the stagnant area and prevent condensation in the section, and the installation of a circulation fan was simulated in the central corridor of exhaust fan no. 6. Simulation analysis was performed on the exhaust fan no. 6, which currently operates as an exhaust fan that exhausts the internal air of the tunnel to the outside, and operates as an intake fan that removes the humid internal air of the tunnel to the outside (Fig. 8). For the corridor where the exhaust fan no. 6 is installed, the installation of a circulation fan that can supplement the intake or exhaust through the exhaust fan no. 6 was fixed. In addition, according to the location of the central corridor of the tunnel, the installation of a circulation fan that can supplement the intake/exhaust flow through exhaust fan no. 6 was simulated. The installation of the circulation fan simulated 3 and 5 units, and the case was designed as follows according to the fan direction of exhaust fan no. 6 and the installation location of the circulation fan (Table 2). The designed case was analyzed and compared with the simulation results of the exhaust (Case 1) and intake (Case 2) using only exhaust fan no. 6 without installing circulation fans.

Meanwhile, the circulation fan in underground structures and buildings, and the fan performance curve for the circulation fan was considered. The fan performance curve is a unique characteristic of a fan. It is a curve showing the fan's airflow when the external pressure conditions are changed for the same fan rotation speed (RPM). The actual fan deliver form the fan performance curve can be reduced by 40-50% depending on the various pressure loads in the field, but in this study, an ideal situation was assumed. The x-axis is expressed as air volume and the y-axis is information about pressure, and the capacity and characteristics of the circulation fan are implemented according to the fan performance curve. The circulation fan considered in this study has a diameter of 400 mm and a capacity of 112 CMM, and the fan performance curve is shown in Fig. 9.

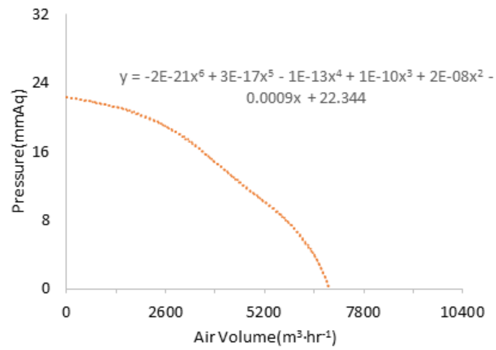

FIGURE 9. **Fan performance curve of target circulation fan (SMP-35, SMATO Co., Korea) applied in CFD model.**

The simulation model was designed for the summer when dew condensation occurred, and the boundary conditions for the simulation model were defined based on the values obtained from the field experiments. First, the internal air temperature was set to 21.3 °C for the section where dew condensation occurred, and the relative humidity was set to 100% to assume the occurrence of dew condensation and high humidity. An internal air temperature of 21.3 °C and relative humidity of 95% were set for the section near exhaust fan no. 6, and an internal air temperature of 23.9 °C. and relative humidity of 89% was set for the section near the inlet vertical duct 7. Assuming a hot summer day, external environmental conditions of 32.5 °C and 40% relative humidity were applied.

Next, a CFD model was designed to simulate the duct installation to remove the relative humidity in the section where the dew condensation occurred. The air conditioning method using ducts means a method to move or circulate air to a specific location by designing a series of ducts and has the advantage that air can flow in and out directly into the target space. Therefore, a duct was designed for the section between the vertical exhaust duct no. 6 and the inlet vertical duct no. 7, which was the section where dew condensation occurs in the target utility tunnel, and the prevention of dew condensation was simulated by removing humid air or supplying dry air to the relevant section to reduce the relative humidity.

As shown in Fig. 10, the duct from exhaust fan no. 6 to the section where dew condensation occurs was designed, and the cross-section of the duct was set to be 900mm high and 300mm wide. The simulation model analysis simulated how

TABLE 2. CFD-Designed cases to proper circulation fan installation.

Case No.	Fan direction	Number of fans	Installation location	Case No.	Fan direction	Number of fans	Installation location
3			R1-1, R1-2	1	Fan 6-exhaust (no circulation fan installed)		
4			L1-1, L1-2	2	Fan 6-intake (no circulation fan installed)		
5			L1-1, R1-1	21			R1-1. R2-1, L1-1 , L2-1
6			L1-2, R1-2	22			R1-1, R1-2, R2-1, R2-2
7	Exhaust		R1-1, R2-1	23			L1-1, L1-2, L2-1, L2-2
8			L1-1, L2-1	24	Exhaust		R2-1, R2-2, L2-1, L2-2
9			R2-1, R2-2	15		5 EA	R1-1, R1-2, L1-1, L1-2
10			L2-1, L2-2	26			R1-1, R1-2, S1, S2
11		3 EA	S1, S2	27			R2-1, R2-2, S1, S2
12			R1-1, R1-2	28			R1-2. R2-2. S1. S2
13			L1-1, L1-2	29	Intake		R1-1. R2-1, L1-1, L2-1
14			L1-1, R1-1	30			R1-1, R1-2, R2-1, R2-2
15			L1-2, R1-2	31			L1-1, L1-2, L2-1, L2-2
16	Intake		R1-1, R2-1	32			R2-1, R2-2, L2-1, L2-2
17			L1-1, L2-1	33			R1-1, R1-2, L1-1, L1-2
18			R2-1, R2-2	34			R1-1, R1-2, S1, S2
19			L2-1, L2-2	35			R2-1, R2-2, S1, S2
20			S1, S2	36			R1-2. R2-2. S1. S2

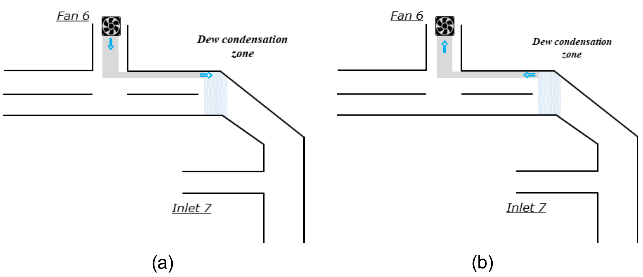

FIGURE 10. Design of CFD model for proper design of ducts for the section of dew condensation in CFD model.

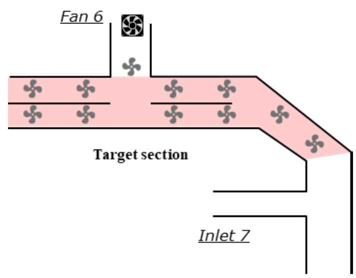

FIGURE 11. Target section to evaluate the increase of air flow velocity according to circulation installation.

to get the dry air on the outside into the tunnel and expel the humid air inside the tunnel to the outside.

The simulation model was set for the summer season when dew condensation occurs in the same way as the circulation fan design model. The internal air temperature of 21.3 °C and relative humidity of 100% were set for the section where dew condensation occurred, and the internal air temperature of 21.3 °C, relative humidity of 95% for the section adjacent to exhaust fan no. 6, and the internal air temperature of 23.9 °C and relative humidity for the section near the inlet 7 were 89 % was set. As for the external environmental conditions, 32.5 °C of external air temperature and 40% relative humidity were applied, which correspond to dry weather in summer in Cheongju-si.

5) EVALUATION OF REDUCING CONDENSATION EFFICIENCY AT TARGET SECTION

The installation of the circulation fan can increase the flow velocity according to the location of the circulation fan, and the effect of removing the stagnant section in the tunnel can be expected by assisting the flow to the nearby exhaust fan. Therefore, by using the numerical simulation model, the improvement on the dew condensation section according to the number and location of the circulation fans installed was studied, and the effect of improving the flow velocity distribution in the tunnel according to the circulation fan installation was calculated. Therefore, the flow velocity distribution was calculated for the central corridor in the vicinity of the vertical exhaust duct no. 6 and the central corridor up to the inlet vertical duct no. 7, including the section where dew condensation occurred (Fig. 11), the lengths of tunnel corridor sections with flow velocity ranges of less than 0.2, 0.2 to 0.3, 0.3 to 0.4, 0.5 to 0.6, and over 0.6 m·s^{-1} were calculated. By comparing the results of each calculation case, it was found that the longer the length of the flow velocity section having a higher flow velocity range, the stronger the flow velocity in the tunnel was formed.

Meanwhile, as a method to evaluate the local ventilation rate of the target facility, the ventilation rate was typically evaluated using the tracer gas decay (TGD) method [38], [39], [40], [41]. The tracer gas concentration method is a method of calculating through the concentration change due to the tracer gas diffusion and is known to show higher accuracy than the mass flow velocity, which calculates the ventilation volume from the total inflow and outflow of the facility [42], [43]. The

TABLE 3. Proper values of RH of each facility in utility tunnel [44].

Object	RH (%)
Main body structure	60-80
Metal pipe	<70
Power cable	<85
Electrical equipment	<75
Personnel safety and health	40-75

TGD method has the advantage of being able to quantitatively calculate not only the overall ventilation volume of the facility but also the local ventilation volume through the dilution trend of the tracer gas for the entire target facility

$$AER_{TGD} = \frac{60ln\left(\frac{C_0}{C_t}\right)}{(t - t_0)} \tag{4}$$

where, AER_{TGD} means the air exchange rate per minute ($AER{\cdot}min^{-1}$) by the tracer gas decay method, C_0 is the initial concentration of the tracer gas (dimensionless), and C_t is the concentration of the tracer gas after t seconds (dimensionless), t means arbitrary time (sec), t_0 means initial time (sec).

In the target utility tunnel, the distance between the inlet and the outlet is as long as 100-150 m, and the entire structure is several kilometres long. Therefore, it is more important to evaluate the local ventilation for stagnant areas than for the total ventilation for facilities. Therefore, the TGD method was applied to the section where dew condensation occurred. After setting the relative humidity to 100% for the target section, the relative humidity reduction efficiency of each case was compared and evaluated by evaluating the amount of relative humidity reduction and reduction time according to the operation of the ventilation system proposed in this study. Furthermore, the previous study [44] presented the appropriate RH index for each facility in the underground tunnel as shown in Table 3. The dew condensation area of the target utility tunnel includes the main body structure, various metal pipes, electrical equipment, and communication lines. Therefore, in this study, the RH index of each facility was compared and evaluated for the effect of reducing the relative humidity according to the installation of the circulation fan and duct system.

III. RESULTS AND DISCUSSION

A. FIELD EXPERIMENT

Dew condensation occurred in the target utility tunnel starting at the end of June, and condensation occurred on most parts of the structures including the floor, side walls, ceiling, and piping around vertical exhaust duct no. 6. Further, in the section between inlet 7 and inlet 9, the dew condensation partially occurred on the bottom wall surface and the pipe. Therefore, the air temperature, humidity, wall surface temperature, and material moisture content in the tunnel were measured for the adjacent section including the section. Measurement results showed that relatively low air temperature and high relative humidity happened at the inlets 5 to 7 and the dew points were lower than those in the other sections. This was because

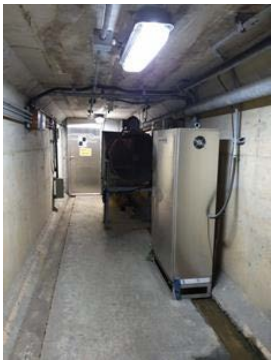

FIGURE 12. Control box installation status near exhaust fan no. 6 that affects the exhaust flow.

the section was constructed deeper than other sections, the air conditioning system does not work effectively, and a stagnated section was formed. When a low dew point was formed due to low temperature and high humidity, dew condensation can easily occur in the tunnel wall having a low temperature under the influence of the underground temperature. Therefore, it was necessary to replace the low-humidity air through the improvement of the air conditioning system in the target section.

B. VALIDATION OF THE CFD SIMULATION MODEL

Using the designed CFD model, the internal flow analysis of the utility tunnel was performed by operating the exhaust fan no. 6. The calculation result of the CFD validation model was compared with the internal flow velocity value obtained from the field experiment according to the operation of exhaust fan no. 6. The comparative locations were the corridor where the exhaust fan was installed and the central corridor in the tunnel (Fig. 12). Because the control box was located near the exhaust fan no. 6, the tunnel cross-sectional area was reduced, and it was found out that the flow velocity point-measured at the site was overestimated (Fig. 13). As a result, all type of turbulence models showed rather large differences compared with field experimental values. Through the CFD model

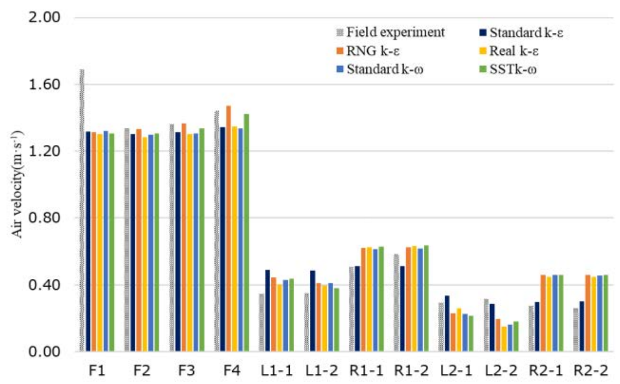

FIGURE 13. Comparative analysis of the internal flow velocity according to the application of turbulence models based on the operation of exhaust fan no. 6.

TABLE 4. Environmental measurement results such as air temperature, humidity, and wall surface temperature for each section of the target underground utility tunnel.

Section	Air temp. (°C)	Dew point (°C)	RH (%)	Surface temp. of side wall (°C)	Surface temp. of ceiling (°C)	Wall material moisture (%)	Condensation
10	22.5	21.3	93.0	22.2	22.4	15.0	-
10-9	22.9	22.1	95.0	22.0	22.0	17.0	-
9	21.8	20.9	94.5	23.6	24.5	13.5	Condensation on floor
9-8	22.2	21.2	93.9	21.5	22.0	12.2	
8	21.8	21.0	95.1	21.3	22.0	16.1	
8-7	22.2	21.4	95.3	21.8	22.2	14.0	
7	23.9	22.0	89.1	22.1	23.0	13.7	
7-6	20.3	20.3	99.7	20.7	21.1	above 20	Condensation on floors, ceilings and side walls
6	19.8	19.8	99.7	21.3	21.7	above 20	
6-5	18.8	17.9	94.5	18.8	18.8	above 20	
5-4	18.9	18.1	95.2	19.0	19.7	14.6	-

calculation, the airflow formed in the central corridor of the tunnel was simulated as 0.29-0.51 $m{\cdot}s^{-1}$. The standard k-ε model showed an error of 0.1 $m{\cdot}s^{-1}$ or less, while the other turbulence models showed an error of 0.2 $m{\cdot}s^{-1}$or less. This is a relatively large error considering the low flow rate. Therefore, the Standard k-ε model showing the highest accuracy was selected, and the accuracy was $R^2 = 0.96$. and RMSE = 0.13 $m{\cdot}s^{-1}$. There was a slight difference in the L1-1 and L1-2 sections compared to the field experiment results. In the case of the site, it was found that the two rows of corridors were combined with the one row of corridors, and a loss of load was relatively generated for sections L1-1 and L1-2. On the other hand, it showed a rather large error at the F2 location.

C. ESTIMATION OF PROPER CAPACITY OF EXHAUST FAN NO. 6

The current Korean design standard for air conditioning system in the utility tunnel suggests that the air flow velocity in the tunnel should be at least 2.5 $m{\cdot}s^{-1}$, while Japan and China standards proposed air flow velocities of 2.0 and 1.33 $m{\cdot}s^{-1}$, respectively. However, the air flow velocities were 0.26 to 0.97 $m{\cdot}s^{-1}$ due to the operation of exhaust fan no. 6 and no. 8 as a result of field test measurement in the target utility tunnel. This measured value falls below the allowable air flow velocity recommended by both domestic and foreign air conditioning system design standards. Therefore, in this study, the capacities corresponding to 2, 4 and 6 times the exhaust fan no. 6 (275.19, 550.38, 1100.76 CMM) were simulated through the CFD model, and the flow velocities for each section inside the computation were calculated.

The calculation results of the flow velocity for each internal section depending on the exhaust fan capacity are shown in Table 4. Based on the table, the internal flow velocity increases with respect to the sections L1-1, R1-1, and L1-2 as the exhaust fan capacity increases. However, for the R1-2 section, the internal flow velocity decreases, which means

TABLE 5. Flow velocity calculation result for each internal section according to exhaust fan capacity using CFD model(Q: Capacity of exhaust fan currently installed).

Section	Air velocity in tunnel according to the capacity of the exhaust fan no. 6 ($m{\cdot}s^{-1}$)			
	Q	2Q	3Q	4Q
L1-1_15m	0.24	1.14	2.89	4.7
L1-1_10m	0.26	1.15	2.89	4.7
L1-1_5m	0.26	1.15	2.89	4.7
R1-1_5m	0.97	0.93	1.27	1.61
R1-1_10m	0.97	0.93	1.27	1.62
R1-1_15m	0.97	0.94	1.29	1.63
R1-1_20m	0.98	0.94	1.29	1.63
L1-2_15m	0.54	0.37	1.34	2.6
L1-2_10m	0.53	0.37	1.35	2.6
L1-2_5m	0.53	0.37	1.34	2.6
R1-2_5m	0.84	0.58	0.48	0.23
R1-2_10m	0.85	0.58	0.48	0.16
R1-2_15m	0.85	0.58	0.48	0.15
R1-2_20m	0.89	0.59	0.53	0.16

that the flow velocity to the R1-1 section corresponding to the first row near the exhaust fan increases. This was because section R1-2 was the second row relatively far from the exhaust fan no. 6, so it received a relatively large amount of friction loss. This means that stagnated area can occur depending on the configuration of the corridor in the utility tunnel, and it needs to be supplemented accordingly.

When the capacity of the exhaust fan was increased 6 times, the internal flow velocity was improved from 1.61 to 4.70 $m{\cdot}s^{-1}$ (excluding the R1-2 section), but still could not satisfy the domestic standard for air conditioning system of utility tunnel. In addition, there was no improvement in the flow velocity in the section more than 30 m away from the

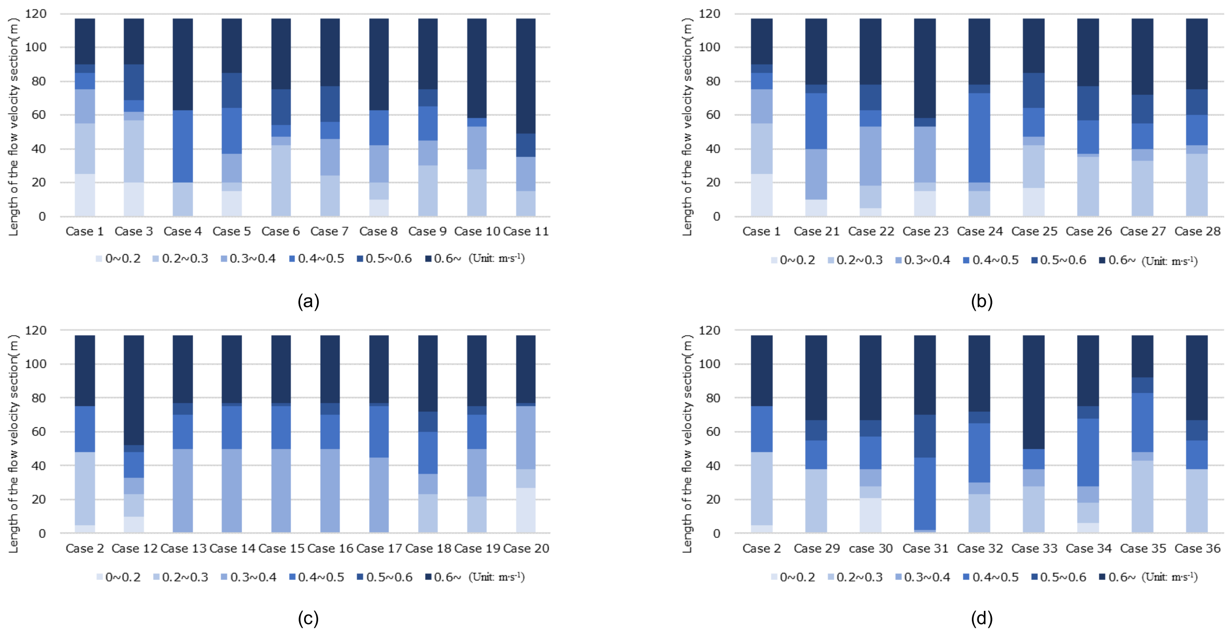

FIGURE 14. **Calculate the length of the flow velocity section between the vertical exhaust duct no. 6 and the vertical intake no. 7 section according to the number of exhaust fan no. 6 and circulation fans and the installed location: (a) Exhaust fan no. 6 and circulation fan 3EA run in the exhaust direction (b) Exhaust fan no. 6 and circulation fan 3EA run in the intake direction (c) Exhaust fan no. 6 and circulation fan 5EA run in the exhaust direction (d) Exhaust fan no. 6 and circulation fan 5EA run in the intake direction.**

exhaust fan no. 6 as the exhaust fan capacity increased. It was found that the influence of the exhaust fan was not sufficient for the section where the utility tunnel had a friction loss due to the bending of the tunnel section, wall friction, etc. and had fallen more than a certain distance from the exhaust fan. It seems that the influence of the exhaust fan was not sufficient. Therefore, it was confirmed that the flow velocity inside the tunnel was increased in the adjacent section to the exhaust fan as the capacity of the exhaust fan was increased, but increasing the capacity of the exhaust fan infinitely causes not only an increase in installation cost but also an increase in power consumption. Therefore, it was judged that it would not be efficient in terms of maintenance. In addition, considering that the improvement effect of increasing the internal flow velocity was insignificant in the section separated by more than a certain distance, it was found that auxiliary equipment such as a circulation fan or duct was necessary.

D. IMPROVEMENT OF AIR FLOW ACCORDING TO THE CIRCULATION FAN

Using a numerical simulation model, the improvement on the dew condensation section according to the number and location of the circulation fans was analyzed. First, the effect of improving the flow velocity distribution in the utility tunnel according to the installation of the circulation fan was calculated. It means that as the length of the section having a high flow velocity range increased, a higher flow velocity inside the tunnel was formed. First, in Case 1 where only exhaust fan no. 6 was operated, the length of the section in which the flow velocity of less than 0.2 $m{\cdot}s^{-1}$ was formed was 25 m, and the length of the section in which the flow velocity was 0.2 to 0.3 $m{\cdot}s^{-1}$ was formed was 30 m. Compared to the case where the circulation fan was installed, the length of the section where a relatively small flow velocity was long. On the other hand, in the case where the circulation fan was installed, it was found that about 50 m section length has a flow velocity of 0.3-0.4 $m{\cdot}s^{-1}$ Whereas, in Case 11, most sections formed the flow velocity of 0.4 $m{\cdot}s^{-1}$.

Next, an analysis was performed on the case where the exhaust fan no. 6 and 3 circulation fans were installed in the direction of the air intake. For Case 2 where the exhaust fan no. 6 was operated as an intake direction, the length of the section in which the 0.2 to 0.3 $m{\cdot}s^{-1}$ flow velocity was formed was calculated to be 43 m. This result confirmed that a longer section where a relatively small flow velocity was distributed compared to the case where the circulation fans were installed. On the other hand, in the case where the circulation fans were installed, a flow velocity of 0.3 to 0.5 $m{\cdot}s^{-1}$ was formed for most sections. Compared to the case using only the exhaust fan, the case in which the exhaust fan and the circulation fans were operated had a shorter section length with a small flow velocity of 0.3 $m{\cdot}s^{-1}$ or less, and the flow velocity inside the tunnel was overall increased. This was because a negative pressure was formed in the target section and the air inside of the tunnel was exhausted to the outside. Next, when exhaust fans no. 6 and 5 circulation fans were operated in the exhaust direction, in Case 1 where only exhaust fan no. 6 was operated, the length of the section where the flow velocity is less than 0.4 $m{\cdot}s^{-1}$ was about 64% of the total length. On the other hand, when 5 circulation fans

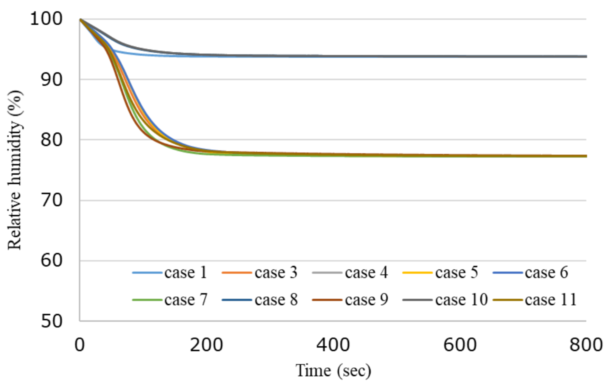

FIGURE 15. Relative humidity reduction graph in the dew condensation section according to time for each exhaust fan no. 6 and circulation fan 3EA operation cases.

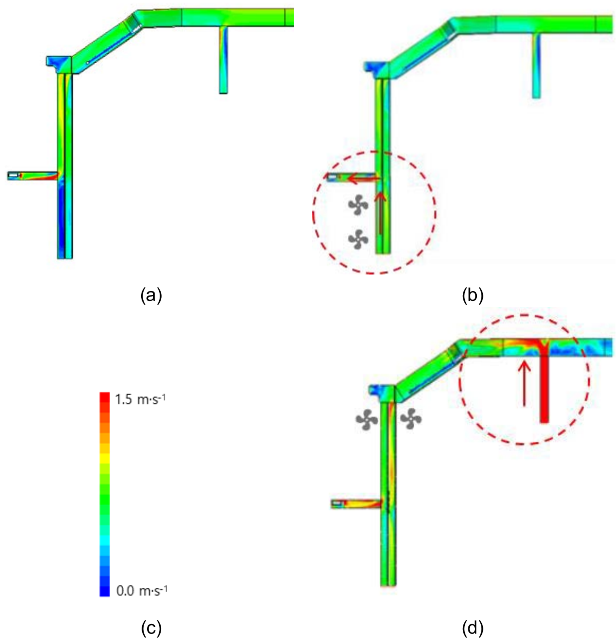

FIGURE 16. Flow velocity distribution according to exhaust fan no. 6 operation and circulation fan 3EA operation in exhaust direction: (a) Flow distribution at 1 m height in Case 1 (b) Flow distribution at 4 m height in Case 1 (c) Flow distribution at 1 m height in Case 9.

are installed, it was reduced to 17-45% of the total length. It was found that when the exhaust fan no. 6 and 5 circulation fans were operated in the direction of intake, the length of the section where the flow velocity of 0.0-0.4 m·s^{-1} could be reduced by about 10% more than when 3 circulation fans were installed.

E. EVALUATION OF CONDENSATION REDUCTION ACCORDING TO AXIAL SYSTEM

In the CFD simulation, when only exhaust fan no. 6 was operated without installing the circulation fans (Case 1), the relative humidity in the dew condensation section reduced up to 93.75%, and in the case of using the circulation fans,

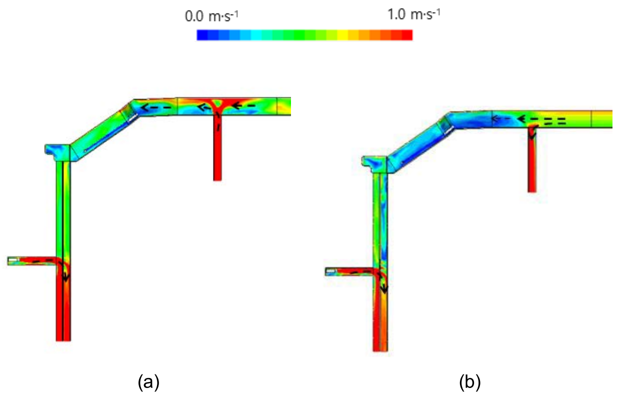

FIGURE 17. Flow velocity distribution according to exhaust fan no. 6 operation and circulation fan 3EA operation in intake direction: (a) Flow distribution at 1 m height in Case 14 (b) Flow distribution at 1 m height in Case 18.

the relative humidity was about 78%, or up to 93%. Case 1 model using only exhaust fan no. 6 and Cases 4, 8, and 10 with circulation fans installed in the directions of the inlet 5 showed a relatively low humidity removal efficiency. Models using the circulation fans installed in the direction of inlet 7 smoothly introduce dry outside air into the dew condensation section through inlet 7. On the other hand, when only exhaust fan 6 was operated, the inflow of external air through inlet 7 was not smooth. In addition, when the circulation fans were installed in the corridor in the direction of inlet 5, the calculated air flowing in from the direction of inlet 5 increased, while the air flowing in the section where dew condensation occurred reduced.

Based on the model calculation, when exhaust fan no. 6 was operated as an intake fan, the relative humidity was reduced by 93.8% while using the circulation fans will reduce the relative humidity to about 93% or about 73% depending on the case. Despite the use of circulation fans, the Cases 12, 16, 18 and 20 models which corresponded to models with circulation fans installed at R1-1, R1-2, R2-1, R2-2, S1, and S2 positions, respectively showed lower relative humidity removal rates compared to the other models. When exhaust fan no. 6 was used as the intake direction, the airflow toward inlet 5 was formed. Further, when the air introduced through exhaust fan no. 6 was directed to the central corridor through circulation fans, the air was channelled toward inlet 5 regardless of the installation position of the circulation fans.

This may be caused by the difficulty of directly inducing the air drawn in from exhaust fan No. 6. It is also likely that the circulation fan that was assumed to be installed on the floor has insufficient capacity to dominate the flow over the entire section of the central corridor in the tunnel. Therefore, in the case where the circulation fans were installed in the corridor toward the direction of inlet 5, the efficiency of inflowing external air from inlet 7 was enhanced by assisting the basic flow of the target utility tunnel. On the other hand, in the case where the circulation fans were installed in the corridor along the direction of the section where the dew

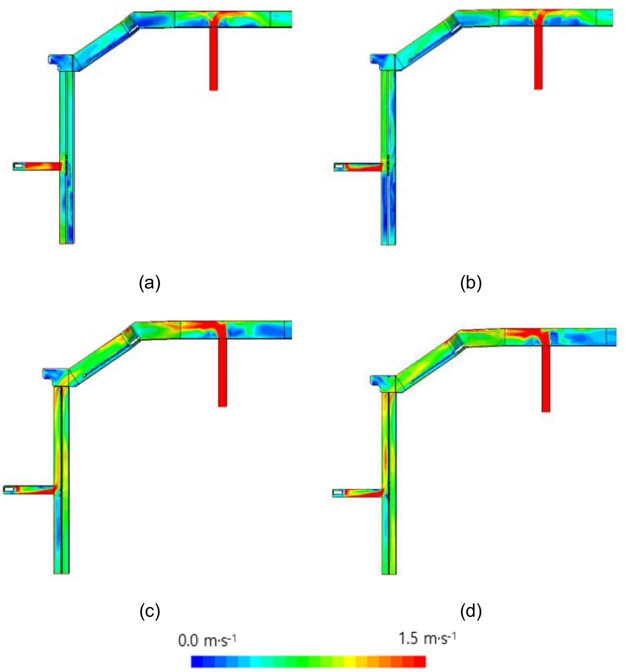

FIGURE 18. Flow velocity distribution according to exhaust fan no. 6 operation and circulation fan 5EA operation in exhaust direction: (a) Flow distribution at 1 m height in Case 23 (b) Flow distribution at 1 m height in Case 24 (c) Flow distribution at 1 m height in Case 28 (d) Flow distribution at 1 m height in Case 22.

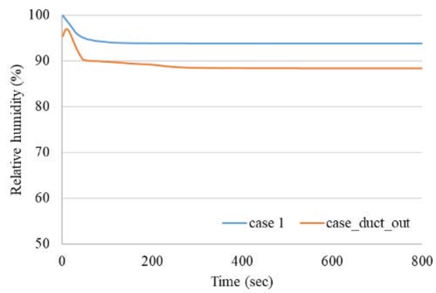

FIGURE 19. Relative humidity reduction graph in the dew condensation section according to exhaust fan no. 6 and duct operation in exhaust direction.

condensation occurred, it was found that the efficiency of inducing external air from inlet 7 was reduced by obstructing the basic flow of the target tunnel. Therefore, in Cases 13, 14, 15, 17, and 19, in which dry external air was induced from inlet 7 for the section in which dew condensation occurred, high relative humidity reducing efficiency was shown, and Cases 12, 16, 18, and 20, in which dry external air was not induced from inlet 7 showed low relative humidity reducing efficiency. As the circulation fans were installed in the exhaust direction, 80% below the proper RH range of the power cable and main body structure was formed, and when the circulation fans were installed in the intake direction, it was formed below the appropriate RH range of 75% for electrical equipment and personnel safety and health.

On the other hand, it was found that similar to the case of installing 3 circulation fans, when 5 circulation fans were installed, the relative humidity was reduced to 93% or 78%. In particular, in the Case 23 model, the relative humidity was reduced to about 93% in the dew condensation section, showing a relatively low reduction efficiency. This was because all the circulation fans were installed at the positions toward inlet 5, so the air flow in the inlet 5 direction was increased, but the air flow from inlet 7 to exhaust 6 including the section where dew condensation occurred was insignificant. Therefore, it was found that regardless of the number of circulation fans installed, if a circulation fan was installed at the position toward inlet 5, the problem of dew condensation in the target utility tunnel will not be significantly improved. When 5 circulation fans were installed in the intake, the removal efficiency showed similar results, such as removing 78-93% of the relative humidity in the section where dew condensation occurred compared to the model with 3 circulation fans. This was similar to the simulation result of installed duct system as the exhaust direction. It was because the basic flow formed in the corridor inside the tunnel was disrupted. Therefore, when the exhaust fan was operated in an intake direction, even if the number of circulation fans installed was increased, the efficiency of removing the stagnant area inside the tunnel could decrease, and the improvement efficiency in the section where dew condensation occurs could also be evaluated low. In addition, compared to the installation of 3 circulation fans, the proper RH range for electrical equipment and personnel safety and health could not be established.

F. EVALUATION OF CONDENSATION REDUCTION ACCORDING TO THE DUCT SYSTEM

The duct system installation using CFD was simulated for the section between vertical exhaust duct no. 6 and inlet vertical duct no. 7, which was considered to be the stagnant area of the target utility tunnel, and where dew condensation frequently occurred. A simulation model (case_duct_out) for exhausting the humid internal air of the section to the outside and a simulation model (case_duct_in) for reducing the relative humidity of the section by directly applying dry external air to the section were calculated. Fig. 18 and Fig. 19 showed the graph for relative humidity reduction in the dew condensation section according to the time for each model. When the designed duct system was operated in the exhaust direction, it was found that the relative humidity in the section where dew condensation occurred was reduced by 89%. This means that the simulated duct exhaust system directly removed the humid air from the section where the dew condensation occurred, but did not induce dry air from inlet 7. Therefore, it was confirmed that the relative humidity reduction efficiency could be improved by increasing the duct exhaust capacity.

Whereas, when the designed duct system was operated in the direction of intake, it was found that the relative humidity

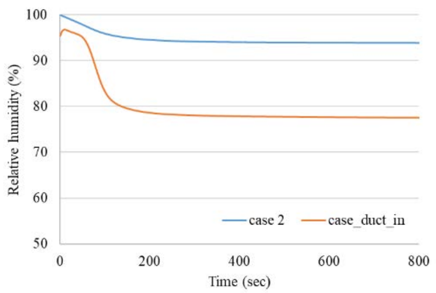

FIGURE 20. Relative humidity reduction graph in the dew condensation section according to exhaust fan no. 6 and duct operation in intake direction.

in the section where dew condensation occurred was reduced by about 78%. Analysis showed that a high relative humidity reduction efficiency was achieved by directly supplying dry outside air to the section. However, the model still had a limitation as it did not remove the humid air and did not form a proper RH range for electrical equipment and personnel safety and health. Therefore, it was necessary to additionally analyze the model calculation and improvement plan for the analysis of these limitations.

IV. CONCLUSION

In this study, the current situation of internal air environment of underground utility tunnel was investigated through field experiment and used for model design of CFD simulation. Analysis of measurements data were used to reduce the occurrence of dew condensation in the tunnel, to design the air conditioning system, and the installation of the circulation fans. The result of the field experiment showed that a relatively low air temperature and high relative humidity were formed at the inlet 5-7 of the target utility tunnel during the summer season. Therefore, dew condensation occurred on the floor and side walls of the corridor, and the need to remove high humidity by improving the air conditioning system was increased. In order to simulate the improvement of the air conditioning system, a three-dimensional CFD model of the utility tunnel was designed. The model was validated for the flow velocity inside the tunnel according to the operation of exhaust fan no. 6. The validation result showed that the Standard k-ε model has the highest accuracy of $R^2 = 0.96$. Using the validated CFD model, the appropriate capacity of exhaust fan no. 6 installed in the section with the most dew condensation was evaluated. When the capacity of exhaust fan no. 6 was increased to 6 times the designed capacity, the internal flow velocity of the tunnel increased to 1.61-4.70 $m \cdot s^{-1}$. However, this did not satisfy the domestic air conditioning system design standards for utility tunnels. Therefore, the improvement effect of the installation of auxiliary equipment such as circulation fans or duct systems were analysed. As a result, it was shown that when 3 or 5 circulation fans were installed in the section where dew condensation occurred, the flow velocity inside the tunnel increased. In particular, when the circulation fans were operated in the exhaust direction and were installed in the stair section, the flow velocity was increased. Next, as a result of simulating air replacement in the section where dew condensation occurred through the installation of the duct system, it was found that the relative humidity was reduced by about 78% when the dry outside air was supplied by operating in the intake direction. The circulation fan proposed in this research required only 1W power consumption per unit, and the duct system uses existing exhaust fans, so there was no additional cost other than the initial installation cost. Through the simulation results of the circulation fan and duct system installation through this study, it was expected that the occurrence of dew condensation in the target utility tunnel can be reduced.

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