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Case Report

Application of virtual product design to the development of HVAC solution for Incheon International Airport Modular COVID-19 testing center

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ABSTRACT

Owing to the spread of COVID-19, the need for an inspection center that can quickly determine whether travelers using the airport are infected has emerged. For rapid determination, not only polymerase chain reaction tests but also antigen-antibody tests and on-site analysis systems are required. However, because it is time- and cost-intensive to construct a building that meets the standards for negative pressure facilities, modular negative pressure facilities are being installed as alternatives. Existing negative pressure facilities have problems such as increased energy consumption due to outdoor air load and condensation due to differences in indoor and outdoor temperatures and humidities caused by excessive external air inflow to achieve the target negative pressure and air change rate (ACH). In addition, owing to the installation of additional devices, additional construction is required to use them for other purposes in the future. To solve these problems, in this study, energy recovery ventilation (ERV) was employed to develop a heating, ventilation and air conditioning (HVAC) solution for the Incheon International Airport COVID-19 Testing Center. To shorten the development period, virtual product design (VPD) using computational fluid dynamics analysis-based design of experiments was performed. Owing to the application of VPD, the Incheon International Airport Modular COVID-19 Testing Center was completed in 2 weeks. The target pressure was measured in all spaces by applying the optimal conditions derived through VPD. In addition, owing to the application of ERV, the ACH of an airborne infectious isolation room exceeded the value suggested by international organizations.

1. Introduction

COVID-19, discovered in December 2019, has since spread rapidly worldwide. To prevent the spread of COVID-19, research has been conducted on the transmission of the virus by heating, ventilation and air conditioning (HVAC) system [1] and waste [2], and each country strengthened the quarantine of personnel entering from abroad [3]. To minimize the time required for quarantine and increase quarantine efficiency, it is imperative to install a COVID-19 testing center at the airport [4]. For the safety of travelers and medical staff who use the test center, it is necessary to have a facility that can generate negative pressure and provide sufficient ventilation in the rooms of the test center. In particular, each country presents design standards for pressure differential and air change rate (ACH) for an airborne infectious isolation room (AIIR) [5]. Notably, an AIIR should be built inside the testing center to isolate emergency patients. However, it is time- and cost-intensive to build an AIIR according to the design standards suggested by each country. Therefore, recently, modular negative pressure facilities have been applied as alternatives in some countries [6,7]. Conditions to minimize virus propagation include maintaining the indoor relative humidity and the pressure difference between rooms. The transmission rate of a virus changes with the change in relative humidity in a room [6,9]. Arundel et al. [8] analyzed that the optimal relative humidity range to minimize virus transmission is 40%–60%. Liu et al. [9] showed that increased humidity reduces the evaporation rate of the ejected potentially virus-laden droplet nuclei. Due to the decreased evaporation rate, floor settling is enhanced and as such, fewer droplet nuclei remain airborne after an expiratory event. When using a room pressure control method by the intake and exhaust fans, it is difficult to maintain a constant indoor relative humidity owing to the
difference in internal and external temperatures and relative humidity. For example, in Korea, winter has a low temperature and humidity, whereas summer has a high temperature and humidity. Therefore, a device for controlling the indoor humidity is required to maintain a constant relative humidity while satisfying the pressure difference and ACH.

Owing to the characteristics of negative pressure facilities, it is time- and cost-intensive to observe changes in internal airflow and pressure distribution through experiments while changing ventilation systems in a large space. Therefore, several researchers have conducted studies on the arrangement of ventilation systems in negative pressure facilities through numerical simulation, thereby reducing the time required for negative pressure facility design and internal airflow analysis [5,10–13]. In particular, Cho [5] analyzed the effect of the strategies of supply and exhaust airflow to improve the ventilation system of an AIIR. In addition, he performed full-scale field experiments and computational fluid dynamics (CFD) analysis to analyze the potential risk of transmission from patients to medical staff in the AIIR and proposed a method to effectively remove airborne contaminants from the AIIR. Tung et al. [10] analyzed the internal airflow and pressure changes with respect to door opening in negative pressure ward. Based on the analysis of numerous cases, the conditions for minimizing the diffusion of airborne contaminants to the adjacent room under the door opening condition were established. Alrebi et al. [11] performed CFD analysis inside an emergency room, analyzed airflow patterns, and studied the effects of changes in the location of ventilation systems. They analyzed the area within the emergency room where virus propagation is most vulnerable using turbulent kinetic energy and velocity profiles and proposed a technique for arranging ventilation systems and space separation to minimize virus propagation. Using numerical simulation, Zhang et al. [12] proposed an optimal ventilation system by comparing the distribution of airborne contaminants in various ventilation systems in an AIIR. In addition, they confirmed that the airborne contaminant removal efficiency has an exponential relationship with the ACH. Guo et al. [13] developed an analytical model of an entire hospital using multizone modeling and conducted a study on the control of the pressure difference in the negative pressure ward in an open door situation. Based on the results of numerical simulation of dynamic situations, such as door opening, they presented a guideline for using a variable air volume damper to reduce the effect of virus propagation caused by opening a door. It should be noted that such simulations of pathogen-laden, turbulent airflow are of a stochastic nature and as such, a very large number of simulations are usually needed to provide statistically relevant results. However, most simulations are computationally expensive, and conducting a large number of simulations may be prohibitively expensive. A novel approach to circumvent such a need has been proposed by Salinas et al. [1] and is based on statistical overloading, where a single Master Simulation would be sufficient to re-provide statistically relevant data.

Most negative pressure facilities create indoor negative pressure by installing additional ventilation fans. In such negative pressure facilities, it is difficult to actively control the indoor humidity; hence, it is difficult to maintain the optimal humidity to minimize the virus propagation mentioned above. Therefore, in this study, the optimal conditions for minimizing virus propagation by generating the desired pressure in the internal space of the Incheon International Airport Modular COVID-19 Testing Center and controlling the humidity using energy recovery ventilation (ERV) with a built-in direct expansion (DX) coil were derived through CFD analysis and then verified in the field. Based on the virtual product design (VPD) of ventilation systems through CFD analysis, the entire construction period of the test center, including the ventilation systems, was realized in 2 weeks.

2. HVAC solution design for COVID-19 testing center

To satisfy the ACH recommended for the AIIR, ACH three times greater than those in existing multiuse facilities is required. Therefore, if an existing ventilation method [Fig. 1(a)] is applied, the external air load increases owing to the excessive amount of external air introduced, and the energy consumption for maintaining the indoor temperature increases. In addition, when high temperature and humidity from outside air flows into the AIIR in summer, an internal condensation problem occurs, and problems such as indoor mold and electric leakage occur.

As shown in Fig. 1(b), if a ventilation system using ERV is used, it is possible to generate the recommended ACH and negative pressure while solving the increased external air load and condensation problems. ERV is an energy recovery device for residential and commercial ventilation.

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**Fig. 1.** Schematics of negative pressure ward ventilation system (a, b), and principle of humidity control by DX coil (c).
systems. It controls the temperature and humidity of the supply air by exchanging the energy contained in the exhaust air. By ERV, the supply air is pre-cooled and dehumidified in summer, and preheated and humidified in winter. When using ERV with a built-in DX coil, it is possible to control the indoor humidity more actively; hence, it is possible to minimize the spread of viruses by maintaining a relative humidity of 40%–60%. Fig. 1(c) shows a humidity control method in the ERV with a built-in DX coil. The humidity control range using ERV with a built-in DX coil is 20%–80%; thus, it is possible to effectively achieve 40%–60% indoor humidity, which can minimize virus propagation. Another advantage of building a negative pressure facility HVAC system using ERV is that the facility can be easily used for other purposes through variable pressure control if there is no need for a negative pressure facility in the future.

The Incheon International Airport COVID-19 Testing Center is a 156 m² mobile modular building with polymerase chain reaction, antigen–antibody testing, and on-site analysis systems and an AIIR for isolating confirmed patients. Therefore, it is necessary to generate negative and positive pressure according to the purpose of each space. Thus, the HVAC system was constructed using two ERVs (Fig. 2). The design pressure conditions of the Incheon International Airport Modular COVID-19 Testing Center are as follows. The pressure in each negative pressure space is 2.5 Pa or less, and the pressure difference compared with the anteroom is 10 Pa or more. For a positive pressure space, the goal is to maintain a pressure difference of 3 Pa or more compared to atmospheric pressure. In addition to the pressure conditions, the AIIR’s target ACH is 12 or more. The ERV with a negative pressure space operated the exhaust flow rate at 120% of the supply airflow rate, and the ERV with a positive pressure space operated the same supply and exhaust flow rate. Based on the HVAC duct design configured as shown in Fig. 2, CFD analysis was performed considering the leakage occurring in the actual building door gap to derive the ventilation duct hole opening/closing condition that satisfies the target pressure conditions. Two ERVs were used in consideration of the ERV’s allowable capacity and ventilation efficiency. The target pressure is created while supply and exhaust air are supplied to each space by the ventilation ducts connected to the two ERVs. The space requiring negative pressure and the space requiring positive pressure are each connected to an independent ERV. The duct is designed considering the diameter and layout that can be installed in the field.

3. Numerical simulation for ventilation strategies

3.1. Numerical simulation methodology

Based on the HVAC duct design layout, the pressure distribution in each space according to the opening and closing of the ventilation duct hole was predicted by CFD analysis. Because the goal is to analyze the flow rate distributed to each space through the ventilation duct and the pressure distribution in each space, a CFD analysis model was created for the ventilation ducts and spaces except for the ERV. Moreover, the wall thickness was ignored in the CFD analysis model.

The flow velocity of air flowing into and out of each space through the duct hole and inside the duct is not large, and the flow characteristics inside the space are not complicated. Therefore, the realizable k-ε model was employed for the turbulence modeling, and the standard wall function was used for the viscous force model by the wall. Variations of air properties according to the temperature of each space were not considered.
considered; air properties under atmospheric pressure at 25 °C were used. For pressure velocity coupling, a coupled method was used, and steady analysis was performed using a pseudotransient method.

For boundary conditions, mass flow inlet/outlet conditions were used based on the flow rates generated in each operating condition in the ERV’s supply and exhaust air ducts. To consider the air flowing into the door gap, the CFD analysis model was created through actual measurement, and the pressure inlet boundary condition was used for this part. Approximately 14 million grids were generated through a grid dependency test, and ANSYS Fluent was employed for analysis.

3.2. Validation test

To determine the suitability of the aforementioned analysis method, the pressure change inside the space was analyzed while changing the leakage area and supply/exhaust airflow rate for the space shown in Fig. 3(a). The grid used for the analysis was created to be the same as the grid resolution determined through the grid dependence test. As shown in Eq. (1) in the ASHRAE Handbook [14], the relationship among leakage area, supply/exhaust airflow rate, and pressure difference is presented based on the orifice equation:

\[
Q = \frac{CA\sqrt{2\Delta p/\rho}} \tag{1}
\]

where,

- \( Q \) = volumetric airflow rate [m³/s]
- \( C \) = flow coefficient
- \( A \) = leakage area [m²]
- \( \Delta p \) = pressure difference across flow path [Pa]
- \( \rho \) = density [kg/m³]

The flow coefficient is for correcting the actual flow rate, and the theoretical flow rate and is based on the flow characteristics and turbulence intensity. Because the flow coefficient changes according to the flow characteristics of the space and is a value obtained through actual measurement, to minimize the effect of the flow coefficient, the exhaust air hole is arranged parallel to the leakage zone (Fig. 3(a)) and the supply airflow rate is selected as the actual supply airflow rate level expected in the space of the testing center. Therefore, in the validation test process, the flow coefficient was selected as 1 in Eq. (1) and compared with the CFD analysis result. As shown in Fig. 3(b), the validation test result of the change of differential pressure in the space according to the change in the leakage area agrees well with the CFD analysis result and the ASHRAE’s correlation.

3.3. Design of experiments (DOE) for numerical simulation

DOE was performed to derive the optimal ventilation duct hole opening/closing condition that satisfies the target pressure of each space. The most efficient statistical analysis can be performed while minimizing the number of experiments using the DOE method proposed by Montgomery [15], which proceeds with the process “Define problem”, “Select response variable”, “Select factors, levels and ranges”, “Select experimental design”, “Run experiment”, “Statistical analysis of the data” and “Verify predicted results”. After defining the purpose of the current experimental plan in the “Define problem” step, the response value of interest, i.e., the dependent variable, is determined in the “Select response variable” step. The third step, “Select factors, levels and ranges” is the step of deriving factors that change the response value of interest and determining the level and range of each factor. In this step, relevant input variables, i.e., key factors, are selected from the factors derived through screening experiments, and the next steps, “Select experimental design” and “Run experiment,” are performed using the selected key factors. Based on the results of the “Run experiment,” the “Statistical analysis of the data” step is performed, which is the statistical significance evaluation and correlation formula derivation step for input variables. Finally, the accuracy of the derived correlation is determined by performing the “Verify predicted results” step, which verifies the predicted value using the derived correlation. Minitab was used for statistical analysis in DOE.

3.3.1. Defining the problem, selecting the response variables & selecting factors, levels, and ranges

The purpose of DOE in this study is to create a target pressure in the negative pressure space and the positive pressure spaces. However, because the positive pressure space can be easily changed by adjusting the ERV flow rate, achieving the target pressure in the negative pressure space was selected as the purpose of our DOE. In the DOE process, the response variable was selected as the average pressure in each space. The opening/closing condition of the ventilation duct hole was selected as a factor, and the level was set to 2 as open/closed. The location of the ventilation duct hole to change the opening/closing condition was selected as shown in Fig. 2 considering the space where supply air must be supplied. A Plackett–Burman design was used to minimize the number of experiments during screening experiments that select a key factor from the primarily selected factors. As a result of the screening experiments, the effect of each ventilation duct hole on the negative pressure space was analyzed (Table 1). In the analysis process, factors with a p-value of ≤0.05 were determined as effective factors for each space based on the 95% confidence level. Based on the effective factors

| Table 1 | Results of the p-value of the screening experiments. |
|---------|---------------------------------------------------|
| E1      | E2 | E3 | E4 | E5 | E6 | E7 | E8 | S1 | S2 | S3 | S4 |
| AIIR 1  | 0.286 | 0.788 | 0.601 | 0.098 | 0.18 | 0.223 | 0.238 | 0.028 | 0.278 | 0.122 | 0.937 | 0.415 |
| AIIR 2  | 0.273 | 0.668 | 0.58 | 0.137 | 0.185 | 0.233 | 0.192 | 0.044 | 0.712 | 0.377 | 0.787 | 0.728 |
| Anteroom | 0.124 | 0.141 | 0.058 | 0.004 | 0.024 | 0.023 | 0.047 | 0.005 | 0.062 | 0.006 | 0.086 | 0.006 |
| Sample Processing Room | 0.036 | 0.099 | 0.132 | 0.372 | 0.795 | 0.276 | 0.683 | 0.114 | 0.38 | 0.244 | 0.438 | 0.171 |
| PCR Room | 0.273 | 0.409 | 0.525 | 0.278 | 0.265 | 0.217 | 0.092 | 0.037 | 0.456 | 0.895 | 0.357 | 0.854 |

**p-value ≤ 0.05**

| Table 2 | Ventilation duct hole conditions for the experimental design. |
|---------|-------------------------------------------------------------|
| Case    | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | S1 | S2 | S3 | S4 |
| 0: Hole Closed | 1: Hole Open |
| 1       | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2       | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3       | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4       | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 5       | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6       | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7       | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 8       | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 9       | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 10      | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 11      | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 12      | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13      | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 14      | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15      | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16      | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
3.3.2. Selecting the experimental design & running the experiment

In the experimental design stage using the selected key factors, a 1/16th fraction full factorial design was used because of the numerous key factors. Because a partial factorial design utilizes a subset of the full factorial design, some main effects and second-order interactions are confounded and cannot be separated from the effects of higher-order interactions. However, in general, partial factorial designs are used assuming that the effects of higher-order interactions can be neglected to obtain information about the main effects and lower-order interactions using a small number of runs in an experiment. Table 2 shows the ventilation duct hole opening/closing conditions derived through DOE. [Fig. 4(a)] was completed by applying the HVAC solution of the optimal ventilation duct hole opening/closing conditions. Differential pressure sensors were installed in the negative and positive pressure spaces shown in Fig. 2, and the pressure in each space was monitored in real time by the main controller [Fig. 4(b)]. As a result of operating the ventilation system of the testing center under the same EVR flow rate and ventilation duct hole opening/closing conditions as in the CFD analysis, the overall measurement result was lower than the analysis result, but the target pressure in the negative pressure space was satisfied. The measured pressure of AIIR 2, Anteroom, and PCR Room was about 2 Pa higher than the CFD analysis value, but the measured and CFD values of AIIR 1 and the Sample Processing Room were similar. These differences are attributable to factors such as duct installation.

### Table 3
Pressure in the negative pressure space by run experiment.

| Case     | Pressure [Pa] |
|----------|---------------|
|          | AIIR 1 | AIIR 2 | Anteroom | Sample Processing Room | PCR Room |
| 1        | −4.4   | −7.6   | −3.5     | −22.7            | −23.9    |
| 2        | −3.3   | −5.6   | −3.3     | −13.3            | −15.3    |
| 3        | −3.2   | −5.3   | −6.0     | −10.7            | −14.8    |
| 4        | −1.7   | −3.4   | −0.6     | −4.2             | −9.7     |
| 5        | −2.5   | −4.4   | −2.5     | −3.9             | −11.2    |
| 6        | −3.0   | −5.1   | −4.8     | −12.1            | −14.1    |
| 7        | −2.3   | −4.2   | −5.6     | −5.7             | −13.2    |
| 8        | −3.4   | −5.8   | −10.2    | −16.9            | −18.5    |
| 9        | −2.6   | −4.5   | −2.0     | −4.6             | −11.8    |
| 10       | −3.4   | −5.7   | −5.0     | −14.5            | −15.5    |
| 11       | −2.5   | −4.5   | −5.2     | −5.9             | −13.1    |
| 12       | −3.1   | −5.4   | −9.3     | −16.3            | −17.9    |
| 13       | −3.6   | −5.9   | −10.5    | −15.8            | −18.9    |
| 14       | −3.4   | −3.2   | −2.2     | −5.9             | −10.8    |
| 15       | −2.2   | −4.1   | −3.4     | −7.7             | −12.2    |
| 16       | −2.5   | −4.4   | −3.9     | −6.4             | −11.6    |

3.3.3. Performing the statistical analysis of the data & verifying predicted results

After performing statistical analysis on the run experiment results using Minitab, the optimal ventilation duct hole opening/closing conditions and the pressure in each negative pressure space were predicted using the derived correlation formula within the 5% error range. The optimal pressure distribution was predicted under the condition that E1, E6, E7, S2, and S4 were opened and the rest were closed. The predicted pressures in each negative pressure space under this condition were AIIR 1: −3.6Pa, AIIR 2: −5.9Pa, Anteroom: −6.2Pa, Sample Processing Room: −15.2Pa, and PCR Room: −16.0Pa. The results were compared with those of the CFD analysis model under the same conditions to verify the predicted values. The pressures of each negative pressure space by CFD analysis were AIIR 1: −3.6Pa, AIIR 2: −5.8Pa, Anteroom: −5.7Pa, Sample Processing Room: −15.2Pa, and PCR Room: −16.1Pa, which values matched well within the error range of the prediction model.

3.4. Numerical solution and field measurement results

The Incheon International Airport Modular COVID-19 Testing Center [Fig. 4(a)] was completed by applying the HVAC solution of the optimal ventilation duct hole opening/closing conditions derived through DOE. Differential pressure sensors were installed in the negative and positive pressure spaces shown in Fig. 2, and the pressure in each space was monitored in real time by the main controller [Fig. 4(b)]. As a result of operating the ventilation system of the testing center under the same ERV flow rate and ventilation duct hole opening/closing conditions as in the CFD analysis, the overall measurement result was lower than the analysis result, but the target pressure in the negative pressure space was satisfied. The measured pressure of AIIR 2, Anteroom, and PCR Room was about 2 Pa higher than the CFD analysis value, but the measured and CFD values of AIIR 1 and the Sample Processing Room were similar. These differences are attributable to factors such as duct installation.
tolerances, door gap tolerances, and room volume errors due to wall thickness. The pressure in the Collection Room, which is a positive pressure space, was 3 Pa, which agreed well with the CFD analysis value (2.7 Pa). Although the ACH of the AIIR was not measured, the AIIR design standard was satisfied with the predicted ACH values of AIIR 1 and AIIR 2 of 21 and 26, respectively, based on the CFD analysis results.

4. Conclusions

To install the Incheon International Airport Modular COVID-19 Testing Center in a short period, VPD was performed using CFD analysis during the HVAC solution development. The error in CFD analysis was minimized by creating a CFD analysis model considering the measured door gap of a module at the testing center and verifying it with the ASHRAE correlation equation [14]. DOE was performed using the verified analysis method, and the optimal ventilation duct hole opening/closing condition was determined using a prediction model derived from DOE. The same conditions for opening and closing the ventilation duct hole selected through VPD were applied to the HVAC system of the Incheon International Airport Modular COVID-19 Testing Center, and the target pressure conditions in each space were satisfied. By completing the Incheon International Airport COVID-19 Testing Center using a modular building in 2 weeks due to the optimal design using VPD, it was confirmed that VPD can be efficiently applied to HVAC solution development.

Unlike in existing negative pressure facilities, ERV was applied to generate the required pressure in the negative and positive pressure spaces, and an ACH value of ≥20 was achieved in AIIRs. Using ERV, it is possible to easily change the indoor pressure condition using the main controller without additional construction when using it for other purposes in the future. Although heating and cooling conditions were not considered in this study, we plan to conduct a study on the optimal ventilation duct hole arrangement and opening/closing conditions considering the comfort of heating and cooling inside negative and positive pressure facilities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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