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Development of a non-contact mobile screening center for infectious diseases: Effects of ventilation improvement on aerosol transmission prevention

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ABSTRACT

Under the global landscape of the prolonged COVID-19 pandemic, the number of individuals who need to be tested for COVID-19 through screening centers is increasing. However, the risk of viral infection during the screening process remains significant. To limit cross-infection in screening centers, a non-contact mobile screening center (NCMSC) that uses negative pressure booths to improve ventilation and enable safe, fast, and convenient COVID-19 testing is developed. This study investigates aerosol transmission and ventilation control for eliminating cross-infection and for rapid virus removal from the indoor space using numerical analysis and experimental measurements. Computational fluid dynamics (CFD) simulations were used to evaluate the ventilation rate, pressure differential between spaces, and virus particle removal efficiency in NCMSC. We also characterized the airflow dynamics of NCMSC that is currently being piloted using particle image velocimetry (PIV). Moreover, design optimization was performed based on the air change rates and the ratio of supply air (SA) to exhaust air (EA). Three ventilation strategies for preventing viral transmission were tested. Based on the results of this study, standards for the installation and operation of a screening center for infectious diseases are proposed.

1. Introduction

In 2020 the World Health Organization (WHO) declared the 2019 coronavirus disease (COVID-19) as a global pandemic, which still persists to this day. COVID-19 is a severe respiratory disease that is highly transmissible and is caused by SARS-CoV-2, which belongs to the Coronaviridae family (Shi et al., 2020; Xie & Zhu, 2020). Most pandemics in the past were because of viruses that caused respiratory infections such as influenza and coronavirus (Lim et al., 2010). Influenza viruses mutate continuously and an antigenic shift occurs every 40 to 50 years, leading to a pandemic situation. In particular, the coronavirus causes a pandemic every 5 to 10 years (Noor & Manibha, 2020). This type of periodic infectious disease places a great burden on medical facilities because the number of infected patients is high. Moreover, it is also important to consider the proportion of infectious disease patients to other types of patients in medical facilities (Grifn et al., 2020). COVID-19 is infectious and is transmitted through the inhalation of respiratory droplets or droplet nuclei produced by an infected person talking, sneezing, or coughing. It can also be transmitted by items exposed to droplets from an infected person, such as clothing, utensils, furniture, and surfaces (Huang et al., 2020a). Therefore, the most effective way to prevent infection is to completely block exposure to droplets (Li & Tang, 2021; Schibuola & Tambani, 2021; Berry et al., 2022; Liu et al., 2021). Efforts have been made to reduce infection by improving, monitoring, and managing indoor pollution levels, temperature and humidity, and requiring the practice of good hygiene, wearing of masks, and the use of personal protective equipment (PPE) by healthcare workers (HCWs) and sanitation personnel (Suvanjan et al.,

Abbreviations: NCMSC, Non-Contact Mobile Screening Center; AR, Anteroom; SCB, Specimen Collection Booth; ER, Examination Room; OA, Outdoor Air; SA, Supply Air; EA, Exhaust Air; TA, Transfer Air; ACH, Air Changes per Hour; HCW, Health Care Worker; CFD, Computational Fluid Dynamics; PIV, Particle Image Velocimetry.

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More recently, the WHO (2020) and the Centers for Disease Control and Prevention (CDC, 2021) have officially acknowledged aerosol transmission of SARS-CoV-2. Therefore, effective ventilation strategies for preventing infection related are necessary (Park et al., 2021; Pan et al., 2021). Medical institutions need to isolate symptomatic patients (including but not limited to fever) from general patients. The screening center plays the primary role in identifying patients carrying infectious diseases. During a pandemic, the number of individuals to be tested in screening centers escalates rapidly. Therefore, temporary or drive-through/walk-through screening centers should be installed to overcome the challenges involved with testing a large number of patients. However, there are no clear criteria and guidelines for the design, installation, and operation of these screening centers worldwide. According to the Ministry of Health and Welfare of Korea, as of January 2022, more than 600 screening centers are in operation in Korea. The main structure of these temporary or mobile screening centers is in the form of a container or tent. These mobile screening centers require direct contact between HCWs and patients, inefficient movement paths, and long waiting hours for patients. Therefore, the risk of human-to-human cross-infection is a major problem in the current structure. More than a year after they became operational, the design, installation, and operation of safe screening centers have not yet been standardized.

In this study, a non-contact mobile screening center (NCMSC) was developed that addresses the problems of existing screening centers and reduces the risk of infection in screening centers. Cross-infection prevention and ventilation control for rapid virus discharge were evaluated for the developed NCMSC. The main aim of this study was to establish a standard for the installation and operation of mobile or temporary screening centers, which are necessary facilities for an effective response against periodic epidemics of infectious diseases.

2. Literature review on the ventilation for COVID-19

Engineering controls should be a major role to prevent the aerosol transmission indoors. The SARS-CoV-2 virus transmission (via airborne by virus-laden aerosols from human breath) occurs mainly in relatively confined environments (Morawska et al., 2020). Escombe et al. (2007) demonstrated that ventilation rate is the important removal mechanisms for airborne infectious factors in buildings. Pease et al. (2022) evaluated the ventilation rate (1.8–12 ACH), influence of filtration (MERV 8-13), and outdoor air intake rate (0~33%). Droplet size specific models were used to estimate the probability of infection. They found that oral droplets responsible for upper respiratory infections generally do not transit central ventilation systems but the smaller bronchiolar and laryngeal droplets do transit between rooms via the air handling system. The Wells–Riley model has been extensively employed in many studies on airborne infectious disease transmission. From a measles outbreak in 1974, Riley et al., (1978) proposed the Wells-Riley model that is most classic model to quantitatively assess airborne infection risk. Because the assumption that the air in a confined space is in steady state and is fully mixed, there are several limitations (Rudnick & Milton, 2003). To overcome this limitation of the Wells-Riley model, many studies have been made (Ko et al., 2004; Qian et al., 2009; Sun & Zhai, 2020). The spatial flow influence factors (SFIF) provide an insight into steady-state airflow field structure and characteristics (Zhang et al., 2006; Wang et al., 2013). Guo et al. (2021) developed a new approach to obtain the spatial distribution for the probability of infection (PI) by combining the SFIF method with the Wells-Riley model. Many researchers have conducted long-term measurement of the indoor environmental quality of office buildings (Choi et al., 2012; Tham et al., 2015; Al Horr et al., 2016; Niu et al., 2022). Liu et al. (2022) investigated the air velocity, air temperature, and particle number concentration in an office under a mixing ventilation (MV) system and a displacement ventilation (DV) system with different ventilation rates. Feng et al. (2021) investigated the impact of barrier heights on the spread of aerosol particles in an open office environment with the well-designed ventilation mode and supply air rate. By combining dilution ventilation (DV) and ventilated cooling (VC), Sha et al. (2021) investigated the operation of the mechanical ventilation system in high-rise buildings, aiming to minimizing the cooling related energy consumption and reducing COVID-19 transmission. Vlachokostas et al. (2022) found that respiratory droplets can...
and do transit through central ventilation systems. For these experiments, respiratory droplet surrogates made of mucus and virus mimics (5-6 µm) were released in one room in a test building. Some researchers also studied the indoor environment of residential buildings and apartments (Sharmin et al., 2014; Huang et al., 2020b). The airborne transmission of infection between dwelling units in high-rise residential buildings was investigated by Gao et al. (2009). On the one hand Liu et al. (2021) applied the inverse design method based on proper orthogonal decomposition (POD) to the design of ventilation parameters for a class room with stratum ventilation. In a hospital (negative pressure) ward setting, some categories (supply and exhaust) were also evaluated, encompassing different air distribution patterns (Cho et al., 2019; Kong et al., 2021). Ventilation interventions are found mainly impacting on the dispersion and inhalation phases of aerosol transmission. The airflow patterns become a key factor in controlling the aerosol diffusion and distribution (Xu et al., 2022).

Until now, ventilation system for infection prevention have been actively studied in offices, residential buildings, patient rooms and classrooms. One of the most important buildings to be managed in a pandemic situation is a screening center. Novel and effective ventilation design, integration with environmental pressure control techniques are challenging. Therefore, the necessity of this study and the utilization of the results have sufficient validity for providing a healthy medical environment. The originality of this study is the development of a safe and new type of NCMSC facility that can respond to the pandemic situation of infectious diseases. The differentiation from other studies is design and improvement of ventilation systems for the cross-infection prevention through the multi-step research procedures and actual uses in the field.

3. Methods

Fig. 1 illustrates the methodology used in this study and its four main components. First, an improved NCMSC was designed. The space configuration and ventilation system, which are key factors in reducing the risk of aerosol infection, were optimized. A ventilation strategy is necessary because the pressure differentials between the rooms and airflow are critical in spaces where negative pressure needs to be maintained. In addition, the ventilation strategy must effectively block the movement of indoor aerosols that transmit SARS-CoV-2 to other spaces and discharge the viral particles quickly. The second step secured the appropriateness of air change rate and room pressure differential through network ventilation simulation to present the rationale for the ventilation system design process to prevent cross-infection in the NCMSC. The final goal of this study is to develop a new type of safe screening center to actually respond to the pandemic and to use it in practice. Therefore, it is the most important that the ventilation performance analyzed by numerical analysis should work similarly in actual screening centers (final products). Several trial (demo) product tests were performed in advance for the multi-zone network simulation and CFD simulation. The critical opening area consists of drainage, door gap, vent, electrical outlet, envelope, and etc., were measured and reasonable average values were reflected in the numerical model. Therefore, the assumptions of the simulation boundary conditions were minimized by reflecting the real situation as much as possible.

The measured data accumulated through the trial product tests were used as the boundary conditions for the numerical simulation, and the feedback of the analysis results and the improvement process of the ventilation system were repeated. Through these preliminary tests, numerical analysis, and on-site PIV tests, reasonable verification of ventilation performance was performed. As a result, a total of 34 NCMSCs have now been produced and are operating in various regions of Korea.

In the third step, computational fluid dynamics (CFD) analysis of the ventilation system was performed using three design alternatives with different ventilation rates (air change rate) and supply air (SA) to exhaust air (EA) ratios. In the CFD #1, the ventilation performance evaluation focused on deriving a comparative advantage alternative between the indoor airflow velocity and the pressure differential. Numerical simulations of the airflow profiles of the ventilation systems with different velocity and pressure differentials can provide a better understanding of virus transmission since there is a lack of experimental data on the spread of viruses by aerosols (Mahshid et al., 2021). The
evaluation of the ventilation performance can confirm aerosol infection prevention. Among the three ventilation strategies, the optimal alternative was derived, and the CFD #2 analysis was to evaluate the particle removal efficiency over time using the virus particle modeling. Based on the numerically-derived optimal ventilation strategy, we experimentally simulated generation of virus particles from a patient and quantified the particle removal efficiency of the ventilation system. In the fourth step, full-scale field measurements were performed under same conditions as the numerical analysis to provide rich experimental data on indoor airflow patterns. Particle image velocimetry (PIV), which can simulate the spread of virus particles, was used. The CFD and experimental measurement results compared and NCMSC operating standards to prevent cross-infection by virus-laded aerosols were proposed.

3.1. Development of a novel non-contact mobile screening center

A NCMSC was developed that uses negative pressure booths to address the ventilation and crowding problems of existing screening centers and enable safe, fast, and convenient COVID-19 testing. The NCMSC is a modular structure that can be quickly moved, installed, and operated in the areas where COVID-19 testing is required. The NCMSC was designed with separate spaces (self-contained booths for specimen collection and for the HCWs to work) with superior airtightness and safety compared to existing mobile screening centers. Moreover, the developed NCMSC can reduce the risk of aerosol transmission between rooms. In particular, a non-contact automated system for the entire testing process was implemented to prevent infection from the source. The developed NCMSC makes screening accessible to patients, reduces the consumption of PPE, and provides adequate protection for HCWs. The NCMSC is a safe medical facility equipped with negative pressure zones, namely the anteroom (AR) and SCB, and positive pressure zones, such as the examination room (ER), as shown in Fig. 2. Moreover, it implements two-stage negative pressure control to prevent virus transmission. The air change rate is set to 12 ACH (CDC, 1994) or above, which is the standard for an airborne infectious isolation room, and the pressure differential is maintained at 25 Pa or above. Subsequently, the ER maintains positive pressure and a high-performance air filter (PM2.5 99.97%) is installed to prevent aerosol infection among HCWs. Taking in 100% outdoor air means exhausting a corresponding amount of the indoor air to effectively balance building pressure requirements, and most buildings do not filter respiratory droplets but exhaust them directly outside presenting an unquantified risk to the surrounding environment.

Fig. 3. Multi-zone network ventilation simulation for the NCMSC (air flow diagram and surroundings): since the size of the line is not an absolute scale and (a), (b), (c) are all individual simulation results, the same size of the line does not indicate the same airflow rate or pressure differential. For example, even if the simulation results of (a) and (b) show the same length, they do not represent the same value.
outlet is important for adequate indoor airflow. Fig. 2 also shows the real-time monitoring and alarm system is used to detect the operating status. Moreover, airtightness is guaranteed even if the ventilation system fails, and transmission between rooms is completely blocked. The SCB has an automatic cleaning system for partial or full space cleaning to enable the disinfection of safety gloves, the space that was occupied by the patient, and the passageways. The HCW is not in direct contact with the patient during specimen collection and protection from viruses (droplets) before and after specimen collection is maintained by periodically checking any glove leakage. An interlocking door system for the pass box was installed in which the airflow (aerosol) is completely blocked by the interlock. A fully automated sliding door was also fitted between the AR and SCB. An automatic swing door was also applied to protect people from droplets and aerosol infection. Because it is a temporary and mobile facility, the initial planning did not consider cooling and heating systems other than ventilation systems.

3.2. Design of NCMSC ventilation systems

Aerosol transmission to other spaces is possible if the pressure differentials between the AR, SCB, and ER is not maintained. In the case of airborne infectious isolation rooms, different standards are applied for the pressure differential depending on the existence of an AR. In most countries, the pressure differential is maintained at approximately 2.5-15.0 Pa (Cho, 2019). However, at the present, there is no definite pressure differential standard for screening centers. In addition, it is also important to investigate the volume of EA needed to maintain negative pressure. The capacity of the ventilation system should be larger than the design requirement to secure airtight performance. The pressure differential is based on the case in which the door is closed and not when the door is opened or with the movement of people. The total air change rate was set to 12-30 ACH to effectively discharge virus particles from the SCB. The screening center ventilation system provides a safe air environment for HCWs and individuals to be tested. Therefore, the appropriate arrangement of the ventilation system SA inlet and EA outlet is important for adequate indoor airflow. Fig. 2 also shows the locations of the SA inlets and EA outlets in the AR and SCB for maintaining negative pressure. The pressure differentials induced by the ventilation system (air balancing) should be analyzed through simulations, and the airtightness of the spaces should be optimized to prevent aerosol transmission and infection between booths in the NCMSC. The indoor space needs to be divided into zones to simplify the CFD simulations for investigating air movement (aerosol transmission) from the SCB to the ER. Three ventilation strategies were applied to evaluate the ventilation performance based on the SA and EA conditions of each room. Moreover, the airflow (air change rate) and pressure differential between rooms were analyzed using CONTAMW, a multi-zone network ventilation model. The basic equation is given by Eq. (1):

\[ Q = 1.29C_d A (\Delta P)^n \]  

where \( Q \) is the flow rate between rooms, \( C_d \) is the discharge coefficient, \( A \) is the surface area of the opening, \( \Delta P \) is the pressure differential, and \( n \) is the flow exponent. In order for the numerical analysis result to be accurate, the boundary condition of simulation model should be validated. Specifically, the pressure differential is mostly depending on both the inflow and outflow airflow rate and the leakage area between rooms. The discharge coefficient was set to 0.6 and the flow exponent was set to 0.5. Moreover, the windows on the outside walls of the NCMSC possessed high airtightness (1 m²/m²h or less at 10 Pa). Case 1 is the baseline ventilation strategy. Specifically, the air change rate for AR and SCB, which are the spaces that maintain a negative pressure, were set to 12 ACH. Meanwhile, the air change rate for ER, which is at positive pressure, was set to 6 ACH. Case 2, the air change rate for ER was 6 ACH, and 30 ACH for AR and SCB. In this case, only the EA system was applied in the AR and SCB, and only the SA system was used in the ER. The transfer air (TA) and pressure differential were set using a relief damper between rooms. Finally, in Case 3, the air change rate was set similarly as in Case 2, but both SA and EA systems were utilized in the SCB.

Fig. 3 shows the results of the multi-zone network ventilation simulation for the airflow rate between rooms and the pressure differential. Airflow rates are displayed with green lines and pressure differences with red lines. The scale for a line has a relative value. Within each simulation result, it is possible to compare the size of airflow rate (m³/h) and pressure differential (Pa) for each room. In Case 1, the airflow rate from ER and AR to SCB was 25 and 45 m³/h, respectively, and the pressure differential can be maintained at -20.9 Pa and -1.7 Pa, respectively. In Case 2, the airflow rate from ER and AR to the SCB was 40 and 135 m³/h, respectively, and the pressure differential can be maintained at -22.6 and -1.9 Pa, respectively. Airflow from the AR is insufficient because only the EA system was functional in the SCB, leading to ventilation performance degradation. Therefore, in Case 3, both SA and EA systems were in operation in the SCB to address the aforementioned issue. The airflow rate from the ER and AR to the SCB was 30 and 70 m³/h, respectively, and the pressure differential can be maintained at -33.4 and -3.8 Pa, respectively. Therefore, the NCMSC was developed based on Case 3. Table 1 shows the ventilation rate and airflow between rooms for each case.

4. Numerical investigations

4.1. CFD #1: Ventilation modeling

In the first CFD analysis, the ventilation performance evaluation focused on deriving a comparative advantage alternative between the indoor airflow velocity and the pressure differential in order to compare the ventilation efficiency according to the location of the supply and exhaust ports and the ventilation rates. A quantitative analysis of COVID-19 viral transmission prevention by an optimized ventilation strategy is needed. As mentioned previously, viral infection routes via
In this study, airflow causing aerosol transmission diffusion of the COVID-19 virus via the NCMSC ventilation system was analyzed using STAR CCM+ CODE. The effects of the airflow velocity and room pressure control on viral transmission were investigated. The safe location of the ER, where HCWs are situated, was also determined. The numerical analysis assumptions, which correspond to the premises for aerosol transmission, are as follows.

CFD simulation assumptions

A1: An Eulerian-Lagrangian approach in this case is more reliable because it allows investigation of the aerosol distribution from the mouth of the infected subject to the environment (D’Alejandro et al., 2021; Motamedi et al., 2022), but it is difficult to make accurate predictions about the droplet nuclei. Numerical analysis is performed without considering the emission from the mouth of the subject.

A2: The droplets are deposited on the SCB walls and floor. Since the SCB is disinfected immediately after the patient is tested, the droplets do not have time to evaporate into droplet nuclei. Aerosol transmission is not considered before the droplets are deposited.

A3: The aerosol transmission only considers the droplet nuclei. Because of P1, the simplified k-ε model is adopted for the aerosol transmission. That is, the airflow behavior is the same as the path of aerosol transmission, and the differential pressure and airflow velocity determine the ventilation performance.

4.1.1. Premises in ventilation analysis

Over two years into the COVID-19 pandemic, the role of aerosol transmission for SARS-CoV-2, which receives only a cursory mention in some infection control guidelines, is still being debated (Tang et al., 2021). The confusion has emanated from the traditional terminologies introduced. This created poorly defined divisions between droplet, aerosol, and droplet nuclei transmission, leading to misunderstandings over the physical behavior of these particles (Tellier et al., 2019).

Essentially, if we can inhale particles (regardless of their size or name), we are breathing in aerosols. The following premises justify the simulation methodology used in this study.

| Premises for aerosol transmission |
|----------------------------------|
| P0: COVID-19 positive persons produce many small respiratory particles laden with virus as they exhale. Some of particles will be inhaled almost immediately within a typical short range distance (<1 m), while droplet nuclei can disperse over longer distances (~2 m) to be inhaled by others. They are all aerosols because they can be inhaled directly from the air (Morawska & Milton, 2020). |
| P1: It is very difficult to know exactly how many particles laden with virus are produced by a COVID-19 infectee because there are too many opportunities for expelling particles (patient coughing, sneezing, talking). Moreover, it is impossible to calculate the volume proportion between droplet and droplet nuclei. |
| P2: The droplets cannot travel long distances, from the SCB to the ER, through ventilation (Wu et al., 2021). |
| P3: The droplet nuclei can travel long distances, from the SCB to the ER, through ventilation. |

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| Case 1 | Case 2 | Case 3 |
|--------|--------|--------|
| Supply in ER | 160 m³/h | 160 m³/h | 160 m³/h |
| Transfer from ER to SCB | 25 m³/h | 40 m³/h | 30 m³/h |
| Supply in SCB | N/A | N/A | 75 m³/h |
| Exhaust from SCB | 70 m³/h | 175 m³/h | 175 m³/h |
| Exhaust from AR | 70 m³/h | 75 m³/h | 75 m³/h |
| Transfer from AR to SCB | 45 m³/h | 135 m³/h | 70 m³/h |
| Lying manikins | Uniform heat flux: 62 W, no slip boundary |
| Walls | 2 and 1 W/m² at ceiling/floor, no slip boundary |
| Bedside | Adiabatic wall boundary condition |
| Grid cells | 8,176,419 |
| Turbulence model | Standard k-ε model |

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CFD simulation assumptions

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A2: The droplets are deposited on the SCB walls and floor. Since the SCB is disinfected immediately after the patient is tested, the droplets do not have time to evaporate into droplet nuclei. Aerosol transmission is not considered before the droplets are deposited.

A3: The aerosol transmission only considers the droplet nuclei. Because of P1, the simplified k-ε turbulence model is adopted for the aerosol transmission. That is, the airflow behavior is the same as the path of aerosol transmission, and the differential pressure and airflow velocity determine the ventilation performance.

4.1.2. Boundary conditions

The boundary conditions of the simulations are listed in Table 2. As shown in Fig. 4, the dimensions of the CFD domain was 4100 × 3000 × 2400 mm (L × W × H) with the SCB, AR, and ER divisions. The EA outlets were located on the ceiling of the SCB and AR to affect avoiding the airflow generated from the door, and the SA inlet was installed in the ER which required positive pressure. Both SA and EA systems were applied in the SCB for effective ventilation. The door dimension was 1100 × 2060 mm (L × H), and the leak area between the door gaps was 0.03 m². The SA flowrate of the ER and the two circular diffusers placed on the upper wall was set to 160 m³/h (6 ACH). An EA outlet was installed on the AR ceiling. In particular, the airflow rate of EA was 30 m³/h (12 ACH) for Case 1, and 75 m³/h (30 ACH) for Cases 2 and 3. Meanwhile, an EA outlet was installed in the SCB with an EA flowrate of 75 m³/h (12 ACH) for Case 1. In addition, two EA outlets were installed for Cases 2 and 3 with an EA flowrate of 175 m³/h (30 ACH). Case 3 applied a SA system in which a circular diffuser was installed on the ceiling with a flowrate of 75 m³/h. Negative pressure control was performed in the SCB, and analyses were performed with all doors closed. The shortage of SA for EA was supplemented through door gaps of adjacent rooms, and the direction of airflow was from the ER to the SCB. Finally, a relief damper was installed to prevent backflow. Two methods can be used to configure the mesh for CFD analysis. The first method creates dense meshes across the entire CFD domain, while the second divides the space and creates different mesh densities. In this study, the mesh density was adjusted by dividing the analysis domain. The total number of grid cells was 8,176,419. The assumptions used in the simulation were as follows: the indoor temperature change was insignificant, viral particles are moved by the indoor airflow, and a no-slip condition was assumed between the phases. The analysis and convergence conditions were set to a residual range of 10⁻⁶, and the turbulence analysis model was based on the standard k-ε model.

4.1.3. Governing equations and the turbulence model

The standard k-ε equation and the second-order upwind scheme were used for analyzing the turbulence equation. The continuity equation in Eq. (2) is based on the law of conservation of mass

$$\frac{\partial}{\partial t} (\rho u_i) = 0. \tag{2}$$

The differential form of the momentum equation based on Newton’s second law shown in Eq. (3) is written as

$$\frac{\partial}{\partial t} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]. \tag{3}$$

Turbulence is a highly nonlinear and complex flow. The turbulence
The particle size of viral aerosols smaller than 5 μm has not been clearly characterized. The composition ratio by best strategy. To date, the air-floating flow for SARS-CoV-2 virus aerosol the particle removal efficiency for the SCB assuming to determine the performance of the three ventilation strategies, we proceeded to analyze the rest of the calculations. Fig. 5 shows the values of the obtained results at thirteen parameters were calculated (airflow velocity at each point of domain. The mesh details of the NCMSC are shown in Fig. 4. CFD model different numbers of cells in baseline layout. The values of these pa also must maintain the lowest grid available to lower simulation time where further increase does not affect the results.

4.1.4. Model validation and grid convergence

To accurately capture the complex flow properties, structured and unstructured grids are implemented in the whole computational domain. The mesh details of the NCMSC are shown in Fig. 4. CFD model also must maintain the lowest grid available to lower simulation time and maintain accuracy. Typically, models will be created in a sequence of coarse, medium, and fine meshes to achieve mesh independency. The total number of grids = 8,176,419 was optimized for ventilation system. Mesh independence study with eleven different numbers of cells performed before starting the current CFD investigation. In each case, thirteen parameters were calculated (airflow velocity at each point of rooms) to obtain the optimum number of cells that will be used for the rest of the calculations. Fig. 5 shows the values of the obtained results at different numbers of cells in baseline layout. The values of these parameters indicate that the optimum number of cells is about 8,000,000 where further increase does not affect the results.

4.2. CFD #2: Virus particle modeling

The second CFD analysis was to evaluate the particle removal efficiency over time using the virus particle modeling. After analyzing the performance of the three ventilation strategies, we proceeded to analyze the particle removal efficiency for the SCB assuming to determine the best strategy. To date, the air-floating flow for SARS-CoV-2 virus aerosol particles has not been clearly characterized. The composition ratio by particle size of viral aerosols smaller than 5 μm when evaporated from a droplet is also unfounded and unknown. Therefore, the particle size was arbitrarily specified by referring to the methodology of a number of existing studies, and the removal efficiency was evaluated based on this. Viral aerosols are discharged through respiratory activities such as coughing, sneezing, and speaking (Redrow et al., 2011). The discharged particles undergo processes such as evaporation, diffusion, and deposition. There is no quantitative information on viral aerosols generated during the sampling process for PCR tests. Coughing is known to be the main cause of infection because of the rapid excretion of aerosols and high particle concentration (Gupta et al., 2009). Therefore, it was assumed that the amount of particles generated during the sampling process was equal to the amount of particles discharged through coughing. A cough can produce up to 3000 droplet nuclei, roughly the same number as speaking in five minutes (Tang et al., 2005; Cole & Cook, 1998). Although the size of particles from humans appears widely, pathogens are mainly distributed in small particles of 5.0 μm or less (Fennelly, 2020). Small particles of 5.0 μm or less can travel in the air for a long time if not removed by ventilation and can enter the human respiratory tract (Siegel et al., 2007). Numerical analysis for droplet nuclei dispersion and transport was performed using the Lagrangian Particle Tracking (LPT) method. This model calculates the fluid flow by the Navier-Stokes method and the diffusion of particles based on the Eulerian-Lagrangian method. Table 3 shows the physical properties and boundary conditions of particles used for CFD simulation.

For coughing, the velocity distribution of the discharged air was set to a maximum of 12 m/s and the mouth area was a circle with an area of 4 cm² (Gupta et al., 2009). The angle of the discharged cough particles was assumed to be 36° (Kwon et al., 2012). The generating virus particles were set to emit a total of 3000 particles of 750 each with a total size of 4 particles of 5 μm or less. It was assumed that a patient emitted once for 0.5 s, and the generated particles were allowed to float without being deposited on the walls, ceiling, and floor of the SCB, and then be exhausted through the ceiling EA outlets. Other than that, the physical boundary conditions of CFD modeling are the same as the previous conditions.

5. Simulation results

In this study, the velocity of air supplied through the SA inlet and door gap, the velocity of air exhausted through the EA outlet, and the
pressure differential between rooms were evaluated for steady-state airflow in the rooms using the standard k-ε model. Then, the ventilation performance, where the virus is assumed to be an aerosol, in the SCB is predicted. Table 4 lists the CFD analysis results for the three ventilation cases implementing different air change rates and SA/EA systems.

### 5.1. Airflow velocity distribution (CFD #1)

Aerosol transmission in the NCMSC can be determined by analyzing the ventilation performance of the SCB and can be indirectly evaluated from the airflow velocity in the rooms. Fig. 6 shows the horizontal airflow velocity profiles at a height of 0.5, 1.5, and 2.2 m from the floor for each case. The air change rates for AR and SCB in Case 1, which only applied the EA system, was set to 12 ACH, as shown in Fig. 6(a). By examining the average airflow velocity distribution for each height in the SCB, the velocities were in the range of 0.0374 to 0.0506 m/s, indicating that the airflow progressed slowly and the air was gradually exhausted. The total airflow rate of EA, AR, and ER were 67.7, 24.2, and 43.5 m³/h, respectively. Specifically, in the case of the AR, the air was exhausted at an airflow rate of 29.0 m³/h with a similar velocity of approximately 0.0365–0.0414 m/s with some of the air moved to the SCB.

The air change rates for AR and SCB in Case 2, which only applied the EA system, shown in Fig. 6(b) were set to 30 ACH. The average airflow velocity profile for each height in the SCB was in the range of 0.0852 to 0.1167 m/s. By examining the average airflow velocity distribution for each height in the SCB, the velocities were in the range of 0.0374 to 0.0506 m/s, indicating that the airflow progressed slowly and the air was gradually exhausted. The total airflow rate of EA, AR, and ER were 67.7, 24.2, and 43.5 m³/h, respectively. Specifically, in the case of the AR, the air was exhausted at an airflow rate of 29.0 m³/h with a similar velocity of approximately 0.0365–0.0414 m/s with some of the air moved to the SCB.

The air change rates for AR and SCB in Case 2, which only applied the EA system, shown in Fig. 6(b) were set to 30 ACH. The average airflow velocity profile for each height of the SCB was in the range of 0.0852 to 0.1167 m/s. By examining the average airflow velocity distribution for each height in the SCB, the velocities were in the range of 0.0374 to 0.0506 m/s, indicating that the airflow progressed slowly and the air was gradually exhausted. The total airflow rate of EA, AR, and ER were 67.7, 24.2, and 43.5 m³/h, respectively. Specifically, in the case of the AR, the air was exhausted at an airflow rate of 29.0 m³/h with a similar velocity of approximately 0.0365–0.0414 m/s with some of the air moved to the SCB.

Table 4

| Room Sections | Air velocity (m/s) | Case 1 | Case 2 | Case 3 |
|---------------|-------------------|--------|--------|--------|
| SCB Z = 0.5m  | 0.0506            | 0.0945 | 0.1756 |
| SCB Z = 1.5m  | 0.0442            | 0.0852 | 0.1781 |
| SCB Z = 2.2m  | 0.0374            | 0.0861 | 0.1236 |
| SCB Y = 0.5m  | 0.0743            | 0.1125 | 0.1201 |
| SCB Y = 1.0m  | 0.0937            | 0.1095 | 0.1454 |
| SCB X = 0.5m  | 0.0526            | 0.1150 | 0.1152 |
| Room average  | 0.0587            | 0.1122 | 0.1786 |
| AR Z = 0.5m   | 0.0414            | 0.0977 | 0.1166 |
| AR Z = 1.5m   | 0.0365            | 0.0903 | 0.1086 |
| AR Z = 2.2m   | 0.0406            | 0.1003 | 0.1110 |
| AR X = 0.5m   | 0.0379            | 0.0857 | 0.1167 |
| Room average  | 0.0410            | 0.0988 | 0.1166 |
| ER Z = 0.5m   | 0.1499            | 0.1469 | 0.1470 |
| ER Z = 1.5m   | 0.1412            | 0.1381 | 0.1405 |
| ER Z = 2.2m   | 0.2825            | 0.2591 | 0.2814 |
| ER Y = 0.5m   | 0.0748            | 0.0838 | 0.0755 |
| ER Y = 1.0m   | 0.0783            | 0.0826 | 0.0818 |
| Room average  | 0.1652            | 0.1664 | 0.1638 |
| Between rooms | Pressure differential (Pa) | Case 1 | Case 2 | Case 3 |
| SCB ↔ AR      | -14.62            | -18.17 | -25.25 |
| SCB ↔ ER      | -1.39             | -1.87  | -3.02  |

Fig. 6. Velocity magnitude contours at different cross-sections (Z = 0.5m, 1.5m and 2.2m) in the NCMSC for different ventilation conditions: (a) Case 1, (b) Case 2, and (c) Case 3.
0.0945 m/s, indicating that the airflow velocity was double that of Case 1, and the air was exhausted at an air flowrate of 169.2 m$^3$/h. At this time, air was introduced from the AR and ER at an air flowrate of 38.7 and 169.2 m$^3$/h, respectively. The air in the AR is exhausted at an air flowrate of 72.5 m$^3$/h with a velocity range of 0.0931 to 0.1003 m/s and some of the air moves to the SCB. Furthermore, the air change rates for AR and SCB in Case 3, which applied both EA and SA systems in the SCB, shown in Fig. 6(c) were set to 30 ACH. The average airflow velocity, SA airflow rate, and EA airflow rate were from 0.1236 to 0.1781 m/s, 72.5 m$^3$/h, and 169.2 m$^3$/h, respectively. The average airflow velocity profile for each height increased by approximately 1.7 times than that for Case 2. At this time, air was introduced from AR and ER at an air flowrate of 29.0 and 67.6 m$^3$/h, respectively. The air in AR was exhausted at an air flowrate of 72.5 m$^3$/h with a velocity ranging from 0.1086 to 0.1166 m/s, and some of the air moves to the SCB. For all cases, both ER and SA systems were applied with an air change rate of 6 ACH, indicating that 154.7 m$^3$/h of air was supplied. Moreover, the airflow rates of each case are different depending on the ventilation conditions of the SCB. The velocities were 0.1499 to 0.2825 m/s for Case 1, 0.1381 to 0.2591 m/s for Case 2, and 0.1405 to 0.2814 m/s for Case 3 based on the examination of the average airflow velocity profile by height, showing a similar pattern for all cases. It was determined that the ER was properly partitioned spatially, and the airflow velocity was not affected by the ventilation conditions of the SCB.

Fig. 7 shows the vertical airflow velocity profiles for each case. The velocities are in the range of 0.0526 to 0.0937 m/s for Case 1, 0.1095 to 0.1150 m/s for Case 2, and 0.1152 to 0.1454 m/s for Case 3 based on the examination of the airflow velocity of the SCB (Y = 0.5, 1.0 m). The ventilation performance in the SCB, where both SA and EA systems were applied, increased accordingly. As for the airflow velocity of AR (X=0.5m), on the other hand, the velocities for Cases 1, 2, and 3 for AR (X = 0.5 m) were 0.0379, 0.0857, and 0.1167 m/s, respectively, showing a similar rate of increase as in the case of SCB. Furthermore, the velocity ranges of ER (Y=0.5, 1.0 m) were 0.0748 to 0.0783 m/s, 0.0826 to 0.0838 m/s, and 0.0755 to 0.0818 m/s for Cases 1, 2, and 3, respectively. All cases were similar, and the velocity was not affected by the ventilation conditions of the SCB. These results are similar to the results of the horizontal airflow profile.

5.2. Pressure differential profile (CFD #1)

The pressure differential is another factor that can affect aerosol transmission prevention in the NCMSC. A negative pressure should be maintained in the contaminated zone (SCB) and a positive pressure should be maintained in the clean zone (ER) to ensure that the aerosol COVID-19 viruses in the SCB do not flow to the ER. Fig. 8 shows the pressure differential profile for heights of 0.5 and 1.5 m from the floor for each case in which the key parameter is the pressure differential between the SCB and ER. It is less likely that COVID-19 viruses migrate from SCB to ER if the pressure is great between these two rooms. The average pressure differential for Cases 1, 2, and 3 were -14.62, -18.17, and -25.25 Pa, respectively. The analysis
showed that the SCB was properly controlled for all cases to maintain the negative pressure. In addition, the prevention of COVID-19 aerosol transmission into the ER is considerably enhanced because the pressure differential increases from Case 1 to Case 3. The pressure differential between the SCB and AR spaces were also tested to evaluate the possibility of aerosol transmission to other individuals waiting outside. The average pressure differential for Cases 1, 2, and 3 were -1.39, -1.87, and -3.02 Pa, respectively. Moreover, both the SCB and AR maintain a negative pressure. However, the pressure differential for Cases 1 and 2 are not within the appropriate range of the recommended pressure differential of at least -2.5 Pa based on the criteria applied to the airborne infectious isolation room (Cho, 2019). Therefore, Case 3 was found to be the most effective method for preventing aerosol transmission.

5.3. Ventilation performance (CFD #1)

Aerosol transmission prevention is enhanced in Case 3 relative to Case 1 because of the wider airflow velocity distribution and higher pressure differential in the rooms. Fig. 9 shows the airflow streamlines across the entire NCMSC.

In all cases, airflow from inside the SCB into the ER was not observed. It is apparent that for the SCB, which applied both SA and EA systems in Case 3, the ventilation is active across the entire room compared to Cases 1 and 2, which only applied the EA system. The airflow velocity results
of 0.0587 m/s for Case 1 and 0.112 m/s for Case 2 were obtained by examining the overall average airflow velocity of the room, indicating that the velocity of Case 2 increased by 1.9 times than Case 1. In addition, the airflow velocity was 0.1786 m/s for Case 3, indicating a velocity increase of 1.6 times than Case 2 and 3.0 times than Case 1. Case 3 does enhance the ventilation performance and facilitates an effective discharge of aerosols carrying the COVID-19 virus.

5.4. Virus (particle) removal efficiency (CFD #2)

From the CFD analysis results, it could be inferred that Case 3 has the best ventilation performance. Therefore, the next step, the evaluation of virus particle removal efficiency, was conducted by applying Case 3 in the SCB. The change in the number of particles of different diameters (0.3, 0.5, 1.0, 5.0 µm according to Table 3) emitted from the patient’s mouth over time is shown in Fig. 10.

Fig. 11 shows the reduction in the distribution of aerosol particles emitted from the patient from t=0.5 s to 500 s under the condition that the sampling room operates the ventilation system of Case 3. It can be seen that the indoor airflow generated by the ventilation system has a significant effect on the dispersion and movement of particles. It is observed that 3000 particles are emitted at t=0.5 s and stay near the patient’s face until t=100 s when the particles are carried by the indoor air flow in the form of agglomerated groups and circle the room. At t=59 s after particle emission, 2/3 of the total particles are exhausted through the EA outlet. There is rapid removal because the particles are exhausted in a group state. It can be seen that the particle groups start to break from t=150 s and disperse and diffuse throughout the room at t=200 s. At this time, the number of particles was about 450, and 5/6 of the total particles were discharged. When the applied ventilation increases the airflow velocity, the dispersion velocity of the particles increases (Mizai et al., 2021).

As the particles diffuse throughout the room after t=200 s, each dispersed particle is exhausted and the number of particles gradually decreases. At t=559 s the particle removal efficiency decreased, but the number of particles was about 30 or less, and 99% of the total particles were discharged. More importantly, it was confirmed that not a single particle was moved to the ER where the HCW is because of the effective ventilation system and pressure differential in the SCB. Therefore, it was possible to completely eliminate the risk of cross-infection to HCWs during the sample collection process. However, in the SCB, even if the ventilation rate is increased to 30 ACH, virus particles can remain until about 10 min and may infect the next patient to be tested. Therefore, it is recommended that the SCB should be disinfected within 10 min after a test before the next patient is tested.

6. Experimental investigations

The airflow pattern based on the application of both SA and EA systems to facilitate ventilation in SCBs was then analyzed experimentally. Based on the CFD analysis, the airflow patterns are different depending on the placement of the SA inlet and EA outlet, airtightness of the structure, and open-close status of the door. The most effective ventilation was achieved when both SA and EA systems operated at an optimal ratio. However, the available experimental data on indoor airflow patterns are not sufficient. Therefore, full-scale field measurements were performed under similar conditions used in the numerical analysis. PIV, which can visualize particles simulating viruses in the SCB, was used for airflow behavior characterization, examination of the leakage area, and for verifying the effectiveness of the developed NCMSC against aerosol transmission. PIV is a non-intrusive measurement method uses optical approaches to characterize airflow and allows various parameter constraints to be adjusted, including image and recording characteristics, laser sheet properties, and analysis algorithms (Li et al., 2017; Cao et al., 2014). In the PIV test, the airflow velocity and the differential pressure between rooms were measured and compared with the results of the CFD #1 simulation for each ventilation strategy. The measurement results provide experimental data on the expected airflow velocity in the SCB that used in verifying the results of the numerical CFD simulation.

6.1. Experimental procedure and setup

The main purpose of PIV test was to measure only the air velocity in the room to evaluate the ventilation efficiency of the SCB. Therefore, enough oil particles were generated to visualize the airflow velocity, and particle generation was not simulated as if a testee is talking or heavily exhaling. Several measurements were conducted to obtain information on airflow patterns between the SCB and ER in the proposed NCMSC. Fig. 12 shows the experimental PIV setup. Two-dimensional flow fields were measured at different camera and laser positions.

First, a camera was installed in the ER, and the laser and oil droplet generator were installed in the SCB. The overall airflow in the rooms adjacent to the tested individual was observed at Position A. For Position B, the laser was installed in the ER and the camera in the SCB. The oil droplet generator was also installed in the SCB so that the droplets come out from the mouth of the manikin, simulating an individual to be tested. Subsequently, the exhaust airflow was observed.

The objectives of Position B measurements are as follows: (1) to determine whether the droplets generated from the patient in the contaminated zone (SCB) are introduced by airflow to the clean zone (ER) where HCWs are staying, (2) to verify whether the contaminants are effectively discharged from the contaminated zone, and (3) to determine whether the droplets generated from the patient are effectively discharged based on the operating conditions of the contaminated zone (SCB). Four different PIV measurements were performed for four different combinations, as shown in Table 5.

The PIV measurement was performed at Position A for Case 2, where only the EA system was applied, and then for Case 3, where both EA and SA systems were simultaneously applied in the SCB as in the CFD simulation (Fig. 12a). Then, the ventilation performance at Position B was examined with the door between the AR and SCB closed and open for Case 3 (Fig. 12b)). In principle, all doors are closed during COVID-19 testing. However, the doors are opened and the room is ventilated after every examination before the next individual to be tested can enter the SCB. Therefore, the ventilation effect in this situation was investigated. The large-scale 2D PIV system used in NCMSC controls the operating components at 3 Hz, including the CCD camera, NdYAG laser, oil droplet generator, synchronizer, and software. Laskin nozzle oil droplet generator is typically used with olive oil. A maximum gauge pressure of 25 psi is typical for most standard pressure systems. The typical mean diameter of the oil droplets is around 1.0 µm. The 3.0 L/min (aerosol flowrate) was continuously sprayed during the test. Table 6 lists the main parameters and settings of the PIV system.
6.2. Measurement results

In Case 2, the PIV experiment was conducted only with the EA system applied in SCB, while both SA and EA systems were used in Case 3. Table 7 lists the time-averaged airflow velocity profiles in the SCB.

As shown in Fig. 13, the pressure differentials of the SCB and ER with the ventilation system turned on are ΔP = -21.8 and -29.3 Pa, respectively. The negative pressure in the SCB was properly maintained for both cases (Cases 2 and 3).

Fig. 14 shows the experimental results for the vertical airflow velocity. The velocity vector consists of two time-averaged velocity components \( V_x (\text{m/s}) \) and \( V_y (\text{m/s}) \) along the X- and Y-axes, respectively. All the results presented are based on the map of the average velocity vectors.

Fig. 14(a) shows the average velocity for Case 2 for Position A (PIV A1). The particle movement velocity in the SCB was found to be very slow with almost no airflow with a maximum airflow velocity of 0.0607 m/s and an average airflow velocity of 0.0098 m/s. The air exhaust efficiency is low because the air flowing in from the AR is not sufficient because of the high airtightness of the structure. The average airflow velocity of PIV A2 in Case 3, where SA and EA systems were applied to the SCB, was 0.0541 m/s, a four-fold increase than that for PIV A1. In addition, the generated particles were smoothly discharged through the upper EA outlet. The make-up air was smoothly supplied to improve the exhaust efficiency. In addition, examination of the leakage area showed that there were no particles generated inside the SCB that escaped through the gap in the wall shared with the ER. Therefore, aerosol transmission is not expected to occur since there is no
airflow from the contaminated zone (SCB) to the clean zone (ER) in PIV A1 and PIV A2. Fig. 14(c) shows the average velocity for Case 3 for Position B (PIV B1). The maximum airflow velocity of PIV B1 was 0.1124 m/s and the average airflow velocity was 0.0536 m/s, indicating that the average velocity of the particles generated in the SCB is the same as that in PIV A1. This is expected because both measurements were performed under the same conditions except for the measurement position. Finally, Fig. 14(d) shows the average velocity for Case 3 for Position B (PIV B2). The same conditions were applied to PIV B2 as PIV B1 except the door to the AR was opened. In this case, the maximum airflow velocity was 0.1747 m/s, the average airflow velocity was 0.1042 m/s.

**7. Discussion**

Aerosol transmission prevention in the designed NCMSC was indirectly evaluated using CFD analysis and PIV measurements based on airflow distributions and pressure differentials. A comprehensive comparison of the ventilation performance of the three ventilation strategies is presented in Table 8.

The multi-zone network ventilation simulation based on the pressure differential between the SCB and ER showed that Case 3 exhibited a 57.9% increase in pressure differential over Case 1, and a 46.0% increase over Case 2. In addition, in the CFD simulation, Case 3 showed a pressure differential increase of 73.3% over Case 1 and 39.0% over Case 2. The results of PIV measurements showed that Case 3 exhibited a pressure differential increase of 34.4% over Case 2, maintaining a pressure differential of approximately -30 Pa that demonstrated a significant improvement in aerosol transmission prevention. The CFD analysis shows that the average airflow velocity in the SCB, which determines the ventilation performance, is increased by 204.3% for Case 3 compared to Case 1 and 59.0% compared to Case 2. Moreover, in the PIV
measurements, the average airflow velocity for Case 3 is four times higher than that for Case 2, indicating an improvement in the ventilation performance. However, the results of the PIV measurements were not in agreement with the CFD analysis results because PIV did not measure the airflow profiles of the entire SCB. Despite this, Case 3 demonstrated the best ventilation performance. Therefore, Case 3 has been demonstrated experimentally and computationally to be effective for aerosol transmission prevention by enabling fast exhaust of aerosol COVID-19 virus.

This study has some limitations. As previously mentioned, numerical analysis do not consider the particle deposition phenomena and their effects on the infection risk. Because of the lack of accurate predictions concerning the droplet nuclei, a simplified CFD analysis model for airflow movement was adopted to optimize the design of the NCMSC ventilation system. Therefore, further studies are needed to investigate the droplet nuclei distribution of the expelled droplets from the mouth of the infected subject to the environment.

8. Conclusions

A non-contact mobile screening center (NCMSC) was developed to reduce the risk of cross-infections in screening centers during COVID-19 testing. The main aim of this study was to evaluate aerosol transmission and ventilation performance against rapid virus discharge based on a pilot project utilizing both numerical analysis and experimental measurements. The results of the study can be used to standardize the design and operation of mobile screening centers. The main findings of this study are as follows.

- In the proposed NCMSC, a space configuration that enables non-contact specimen sampling between HCWs and tested individuals was implemented. Pressure differential control to maintain negative/positive pressure in different NCMSC spaces was implemented. In addition, the proposed SCB design allows sufficient ventilation so that the room can be disinfected for safe use by the next patient to be tested.

- Design optimization was performed using three alternatives involving different air change rates in each room and applying the SA/EA ventilation strategy to prevent the transmission of the COVID-19 virus in the NCMSC.

- Since aerosol transmission is an acknowledged mode of transmission, quantitative analysis of airflow velocity profiles and pressure differentials enables indirect evaluation of the virus transmission route and NCMSC ventilation performance.

- CFD analysis revealed that aerosol transmission prevention was the most effective in Case 3, where the negative pressure in the SCB must
be maintained at a ventilation rate of 30 ACH and a pressure differential of -25 Pa or more with the ER using both SA and EA systems. Compared to Case 2, in which only the EA system was applied under similar ventilation rate conditions, the airflow velocity in the room for Case 3 increased by approximately 60%. Moreover, compared to Case 1, in which only the EA system was applied with a ventilation rate of 12 ACH, the airflow velocity for Case 3 more than doubled. This demonstrated that applying Case 3 improves the ventilation performance.

For Case 3, out of 3000 particles generated by a patient, not a single particle escaped from the SCB to the adjacent room, and more than 99% of the particles were removed by the EA/SA system after 559 s. PIV experiments for Case 3 show that a pressure differential between the SCB and the ER of -30 Pa or more was maintained, and aerosol transmission prevention was excellent compared to Case 2 where the pressure differential was -22 Pa. Moreover, the airflow velocity in the SCB for Case 3 is four times greater than for Case 2. The ventilation performance is enhanced by applying Case 3.

Based on the results of this study, ventilation and space design standards for COVID-19 screening centers are proposed. Specifically, negative pressure must be maintained in the SCB with respect to the other spaces in the NCMSC to prevent aerosol transmission between HCWs and individuals to be tested. A ventilation rate of 30 ACH, and a pressure differential of -15 Pa or higher is recommended. In addition, the simultaneous application of both SA and EA systems is effective in facilitating a smooth discharge of the virus from the enclosed spaces. It is also recommended that the SCB should be disinfected within 10 min after each test before the next patient is allowed to enter the SCB. Additional research is needed to evaluate the complex impact, such as reflecting a reasonable cooling and heating system that minimizes the effect on airflow.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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