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Thermal Performance Improvement and Contamination Control Strategies in an Operating Room

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ABSTRACT

The operating room is categorized as a positive bio-cleanroom that provides thermal comfort and good indoor air quality (IAQ) to support the surgery process. The heating, ventilation, and air conditioning (HVAC) system plays a critical role in the health protection regarding IAQ, i.e., thermal performance, ventilation rate, pressurization, filtration, airflow distribution, etc. However, the HVAC system in the operating room is operated for 24 hours year-round with intensive energy consumption. Energy-efficient approaches for the HVAC system is also quite challenging in term of thermal performance and contamination control to meet the design specifications. In this study, a positive pressurized operating room has been carried out through the field measurement test and numerical simulation extensively. The field measurement test results revealed the ventilation rate is over design with 11,224 CHM compared to the design specification is 8,000 CMH. The energy-efficient approach by reducing the face velocity of the HEPA filter was carried out by reducing the velocity from 0.35, 0.30, 0.25 (m/s), respectively, for energy-saving concerns in order to meet the thermal performance and minimum contamination control requirement. The results revealed that by decreasing the face velocity, thermal performance could be achieved in accordance with standard specifications. In addition, the contamination control also could be conformed to thermal performance.

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1. Introduction

A wide variety of bacteria and infectious airborne contaminants (viruses) can be transmitted through the air, which is found in many hospitals [1], especially in the operating room that requires the full attention of controlled work environments providing a comfortable and healthy environment for both the surgical staff and the patients [2]. The heating, ventilation, and air conditioning (HVAC) systems have an important role for health care facilities in providing clean air, proper air conditioning, and also in eliminating contaminants [3]. In order to maintain a healthy environment for patients and healthcare workers, the level of thermal comfort and decent indoor air quality should be controlled following the valid regulation. ASHRAE standard 170 [4] mentions several rules that must be observed in the operating room, including the number of air changes per hour, airflow distribution, room pressurization, and filtration. ASHRAE standard 62 [5] states that indoor pollutants can affect the activities of occupants; one example is carbon dioxide. Total carbon dioxide exposure in the room must be less than 1000 ppm; this will keep health workers in good condition and stay focused. A high concentration of carbon dioxide could cause shortness of breath, headaches, confusion, and other symptoms while in the room.

Furthermore, many researchers also conducted studies by changing the velocity of supply air to control contamination in the operating room. The relatively low velocity in the operating room will affect the concentration of the microbe-carrying particles (MCP) and the velocity of deposition in the room. This indicates that there may be a risk of microbiological contamination from surfaces exposed to areas that have low speeds, such as under the lights during surgical procedures [6]. In addition, the position of the operating lightings can affect the movement of particles, and it was also shown that higher supply velocity (≥0.38 m/s) caused flow disturbance [7]. The accumulation of airborne BCPs under the operating lightings leads to a high risk of infection to patient safety [8]. Another research, with four different air supply velocities (0.16, 0.24, 0.29, and 0.33 m/s), was conducted by Liu et al. [9]. Greater cleanliness in the surgical area can be ensured by an air supply velocity greater than 0.24 m/s. Whereas, when the air supply velocity continues to increase (0.33 m/s), it will increase the bioaerosols deposition in the surgical area.

The supply air velocity should be optimally designed to conform with the energy consumption for energy saving. The HVAC system in the operating room is operated for 24 hours year-round with intensive energy consumption [10]. HVAC systems in operating rooms are operated under full load even when the room is not occupied. For energy-saving concerns, a preliminary study of numerical analysis has been conducted to evaluate the air velocity distribution and concentration contours while conducting the reducing air changes rate per hour (ACH) approach in the unoccupied operating room at a hospital [11].

Computational Fluid Dynamics (CFD) simulation can be used to predict airflow and can also control contamination. The solution given by CFD to these predictions is quite effective as it can overcome the limitations of the experimental method of direct measurement [12]. Field measurements are carried out as the basis of the parameters that will be used as the boundary condition in CFD simulation [13]. In this study, CFD simulations were conducted to find the potential of HVAC systems to control air contamination, a comfortable environment for occupants, and the possibilities of energy-efficient approaches in the operating room. This simulation is based and verified on field data collection.

In order to achieve a good environmental condition, the concentration decay method could be used to assess indoor ventilation efficiency. Particle experiments and tracer gas experiments are widely used. However, most researchers simplify the pathogen as particles or gaseous without considering their biological characteristics [14]. Chung [15] used carbon dioxide (CO_2) as a pollutant to assess indoor ventilation efficiency. Tracer gas is injected into the space and mixed into the air. The decrease of tracer gas concentration is recorded during a given period [16]. This study investigates the thermal performance and contamination control in order to find the performance improvement that was conducted through a comprehensive field measurement test as well as numerical simulation analyses.

2. Methodologies

2.1. System Description

The operating room is normally categorized as a positively pressurized bio-cleanroom which ensures a critical environment for both thermal comfort and infection control concerns that need to comply with applicable standards and regulations. The dimension of the investigated operating room is at a length of 6.3 m, a width of 6.0 m, a height of 3.0 m, and a total area of 37.8 m^2. The function of this operating room was heart surgery. HEPA filtered the supply air with a total of 15 units located in the center of the ceiling. The operating room was classified into ISO 7 [17] with a maximum of particles per cubic meter at a size 0.5 μm is 352,000 or equal to the Federal Standard 209E [18] with a cleanliness level of 10,000 particles per cubic feet. The design specification of indoor environmental parameters in the investigated operating room included temperature of 22±2°C, relative humidity at 30–60%, and pressurization at 5 Pa. Figure **1** displays the HVAC system in the operating room, (a) filter in air handling unit (AHU) system to filter dirty air coming from the mixing air cabin, (b) cooling coil to cool down the temperature of the air with chilled water on the coil that comes from the process of cooling the water by the chiller, (c) heating coil for the process of heating and humidifying the air to fit with the design of the operating room, (d) fan to supply the air into the room, (e) high-efficiency particulate air (HEPA) filter to filter the air particles with the efficiency of HEPA filters over 99.97% (above 0.5 μm), so that the air entering the room becomes clean, (f) return air; the air coming from the room will draught to the AHU system and supply the operating room.

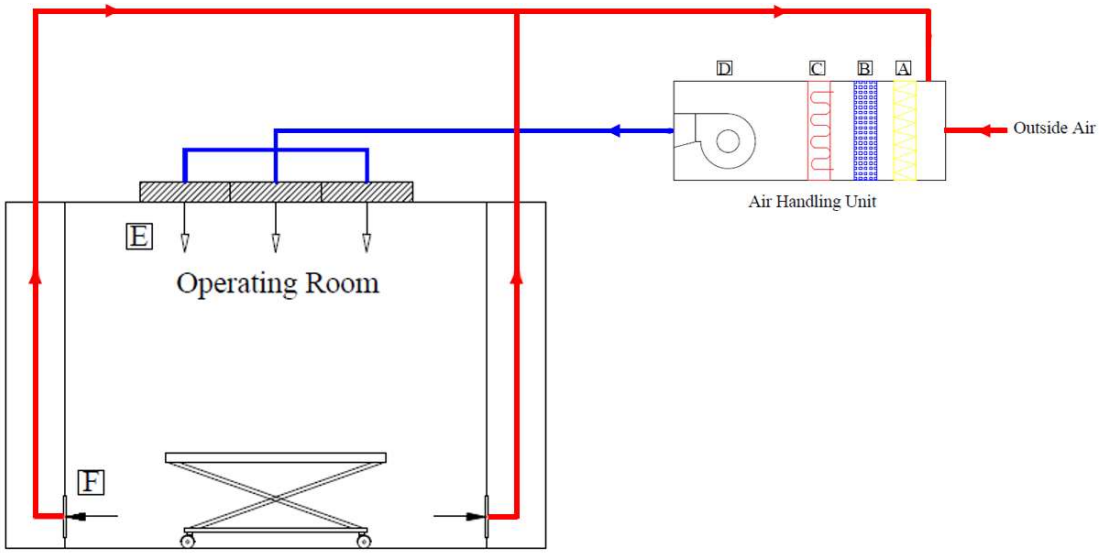

Figure 1: Layout of the investigated biotechnology cleanroom.

2.2. Field Measurement Test

This operating room requires a clean environment to prevent contamination in the room because the surgical process is sensitive to environmental parameters in the room, including temperature, relative humidity, air particles, and room pressurization. In this study, to determine the indoor environmental parameters of this operating room, field measurements are needed to examine the indoor environment parameters of the investigated operating room during an unoccupied period (at-rest). Parameters taken are air flow rate, particle contamination, room temperature. The apparatus tests for field measurement are as follows (1) Airflow rate; a TSI model PH-731 was employed to monitor the velocity of each HEPA. A HEPA dimension was measured to get the airflow rate. After that, the air supply velocity with velocity matrix to HEPA was measured. (2) Particle counter is used to count particles in the air of an operating room. Finding out the number of particles in the room can be carried out using Met One 3413, and it was measured at the height of 1.2 m above the floor within one minute recorded. (3) Temperature and relative humidity in the room are very influential on objects in a room. TSI model 9565P was used to find out the temperature and humidity value in this operating room, and it was measured at

the height of 1.2 m above the floor with three times the measurement data. Furthermore, the measurement data will be validated with the results of numerical simulation. The results of this measurement data will be the basic parameters for ensuring that the operating room is in accordance with the desired design.

Table 1: Apparatus for field measurement test.

Parameters	Apparatus Model	Operative Range	Accuracy
Velocity Pressure	TSI PH-731 (1)	0.125 - 12.5 (m/s) Differential ± 3735 pa	3% 2%
Particles	Met One 3413 (2)	0.3, 0.5, 1, 3, 5, 10 μm	5%
Temperature Humidity	TSI 9565P (3)	-10 ~ 60 (℃), 0 - 100 (%RH)	0.3℃ 3%RH

2.3. Numerical Simulation

Computational Fluid Dynamics (CFD) was conducted to investigate the thermal performance, airflow distribution, and concentration of airborne particles. The operating room simulation was performed using the Ansys Fluent software version 2020 R2 [19]. ANSYS fluent provides several equations to solve the problems, including laminar and turbulent fluid flow problems, incompressible and compressible fluid, and other problems. In order to solve the flow and temperature fields of the problem, ANSYS solves conservation equations for mass, momentum, and energy. The equation for mass conservation is written as follows.

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

$$\nabla = \frac{\partial}{\partial x}\vec{l} + \frac{\partial}{\partial x}\vec{j}\frac{\partial}{\partial x}\vec{k} \,. \tag{2}$$

Equation 1 is the general form of mass conservation equation for incompressible and compressible flows. Where the t, ρ, $\vec{v}$, ∇ are time, density, velocity, gradient operator, respectively, and S_m is the mass added to the continuous phase from the dispersed second phase and any user-defined sources. ANSYS fluent defined ∇ according to the cartesian coordinate in Equation 2.

$$\frac{\partial}{\partial}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \,, \tag{3}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{4}$$

$$C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right] , \eta = S\frac{k}{\varepsilon} , S = \sqrt{2S_{ij}S_{ij}} \,, \tag{5}$$

The turbulent model used in this study is a realizable k-ε turbulence model where the flow features include strong streamline curvature, vortices, and rotation. In addition, some researches have proven that this model provides the best performance of all the k-ε models. The modeled transport equations for k and ε in the realizable k-ε model are written in Equation 3, Equation 4, and Equation 5. G_k represent the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy, Y_M is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, C_2 and $C_{1\varepsilon}$ are constants, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively. S_k and S_ε are user-defined source terms. In order to understand the heat transfer effect of the model, Equation 6 are used where Q is heat

transfer capacity(kW), $\dot{m}$ is the mass flow rate(m^3/s), cp is specific heat (kJ·K/kg), and ΔT is the temperature difference.

$$Q = \dot{m} \cdot cp \cdot \Delta T \tag{6}$$

The 3D geometry of the operating room is made based on the actual size and situation of the room, as shown in Figure **2**. The field measurement data will be used to validate the data with the numerical simulation. The temperature and velocity of the HEPA filter have been measured through field measurement tests to provide reliable measurement data as a boundary condition for the CFD simulation. Furthermore, it will be studied in different scenarios in order to find the best performance.

The steady-state and transient numerical simulations have been carried out with the realizable k-ε as the turbulence model. Transient conditions are used to monitor the reduction of the concentration in the operating room. The steady-state condition is used to validate the field measurement data for temperature and velocity. The iterative coupling calculation for this stage is solved by the SIMPLE (Semi-Implicit Method for Pressure Linked Equation) method. The numerical simulation was calculated until it reached the residual of 10^{-5} to 10^{-6} to produce more precise results.

A tracer gas experiment was carried out in this study. The pathogens are simplified as particles or gaseous without considering their biological characteristic [20]. Carbon dioxide (CO_2) was selected as a pollutant to assess indoor ventilation efficiency and environmental conditions in the operating room with different scenarios. The boundary conditions of numerical simulation are shown in Table **2**. The initial condition of the CO_2 inside the operating room was set at 1,500 ppm. The CO_2 concentration in the outdoor atmosphere is about 400 ppm, which will be used as the concentration value for supply air from HEPA [21]. The concentration decay will be monitored within 500 seconds and recorded every 25 seconds.

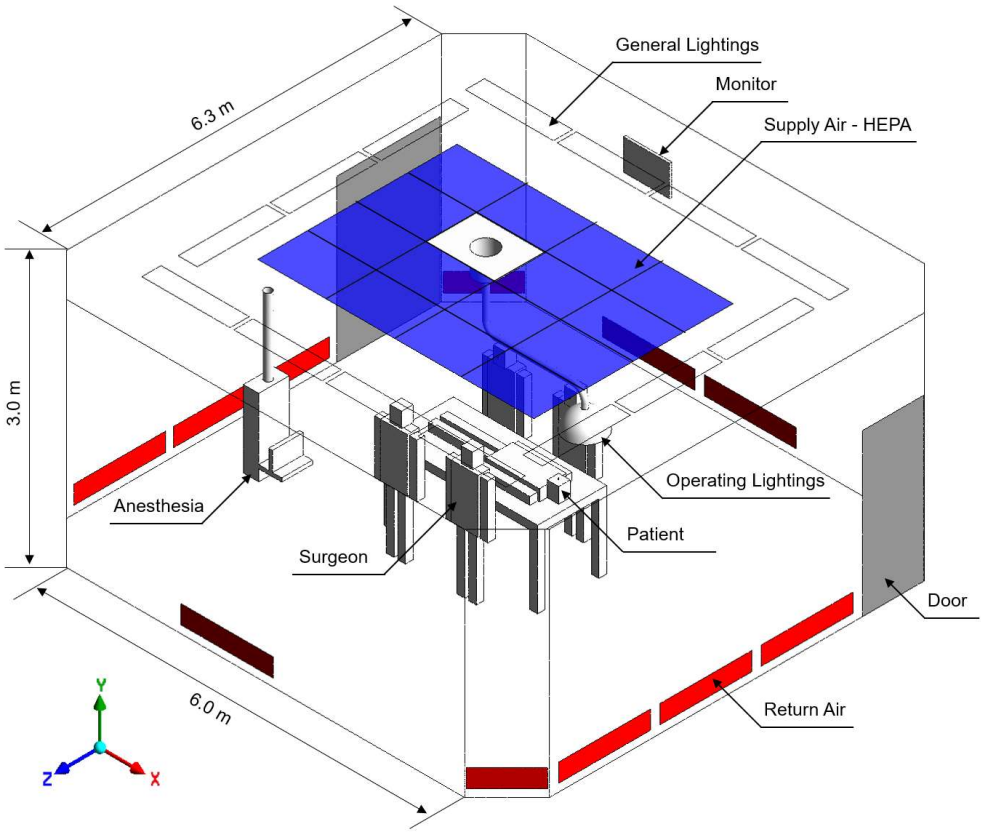

Figure 2: The geometry model of the investigated operating room.

Table 2: Boundary condition for numerical simulation.

Parameters	Type	Value
Supply Air	Velocity Inlet	Velocity: 0.355 m/s Temperature: 20.2°C Concentration: 400 ppm
Return Air	Pressure Outlet	Temperature: 24°C
Patient	Wall	Heat Flux: 17.45 W/m^2 [22]
Surgeon	Wall	Heat Flux: 33.55 W/m^2 [22]
General Lightings	Wall	Heat Flux: 288 W [22]
Operating Lightings	Wall	Heat Flux: 320 W [22]
Monitor	Wall	Heat Flux: 20 W/m^2 [22]
Anesthesia	Wall	Heat Flux: 170 W [22]
Wall	Wall	Heat Flux: 4.17 W/m^2
Doors	Wall	Heat Flux: 5.26 W/m^2

During the simulation process, the parameters could change the level of accuracy as the number of elements in the mesh will increase the accuracy of the simulation results [23]. However, this requires a long time and sufficient resources. The grid test was conducted in this study to obtain the number of elements to meet the appropriate meshing process. Three different numbers of meshes were considered in this study, 994,474 elements for coarse mesh, 1,049,269 for medium mesh, 1,115,758 for fine mesh. Furthermore, the simulation results with the number of different elements will be validated with data from field measurements to validate its accuracy. The data validation used in the study is based on the results of the field measurements test of temperature and velocity data. There are seven temperature measurement points in the field measurements and compared with the numerical simulation results. Validation between simulation results with the three meshes and field measurements can be seen in Figure **3**. The type of mesh that is closest to the measurement data is "fine"; it has an average error value below 1%. Based on these findings, "fine" was used for further investigation.

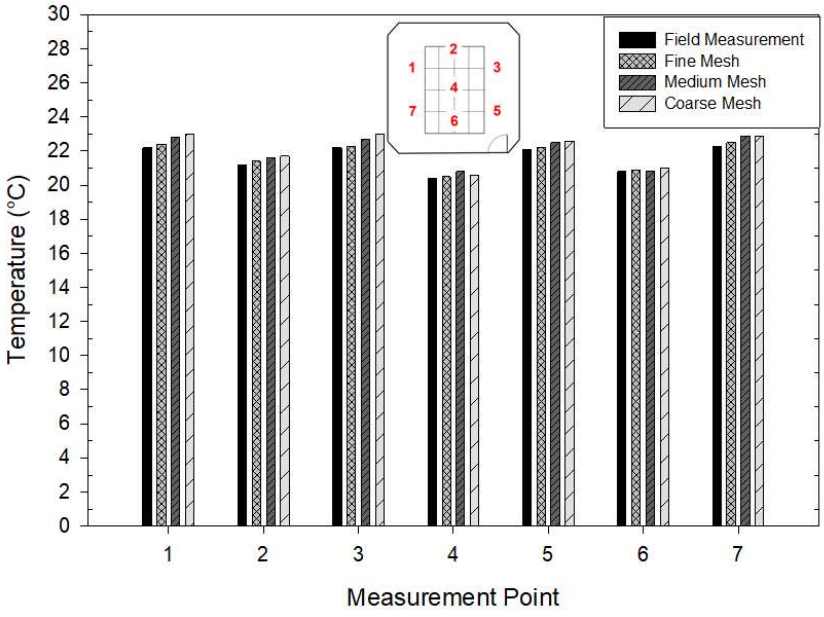

Figure 3: Validation between the field measurement and numerical simulation

3. Results and Discussion

3.1. Experimental Results

Data retrieval has been carried out in accordance with applicable regulations. Field measurement data were collected at the condition of the room without occupants (at-rest condition). Data parameters taken can represent the quality of the operating room by applicable standards, such as the velocity of the supply air, ventilation rate, particle counts, pressurization, temperature, and relative humidity, which should be appropriate.

The specifications of indoor environmental parameters in the investigated operating room include temperature at 22±2℃ and relative humidity at 50±5%. The experimental results show good data in the range of acceptance, for temperature is around 20.4℃ to 22.3℃, and relative humidity is around 46.3% to 53.7% in 7 points measurement. The average velocity from supply air is 0.355 m/s. The total airflow rate in the operating room is 11,224 CMH, while the design airflow rate required in this operating room is 8,000 CMH. It was revealed that the airflow rate is over design. Therefore, it is necessary to reduce the velocity of the air supply from 0.35 m/s to 0.26 m/s to meet the operating room design standard, which could also result in saving energy. The higher ventilation rate and fewer particle counts in the cleanroom reveal the higher cleanliness level for the cleanroom. The operating room is classified as ISO 7 (class 10,000). According to the field measurement results, the particle at size 0.5 μm was counted less than the standard of 352,00 particles/m3. Another experimental data on pressurization, the ASHRAE standard 170, mentions that the pressure differential shall be maintained larger than 2.5 Pa. The measurement data for the pressure difference in this operating room is 10.6 Pa. This certainly shows a number that is higher than the standard given. Basically, the operating room should have a positive pressure due to contaminant-free and to prevent cross-contamination. Therefore, the pressure in this room is greater than the standard. However, this could cause the energy consumption of the air conditioning system to increase substantially.

3.2. Airflow and Temperature Distribution

The existing face velocity from the supply air is at 0.355 m/s, which has been carried out from the field measurement test. According to the design standard, there is an over-supply design. The higher ventilation rate will result in a higher cleanliness level, and also, the temperature will be reached quickly. However, it could consume more energy. Three different face velocities were investigated to find the optimal ventilation rate that could be matched between cleanliness level and thermal performance.

Figure **4** depicts the results of the velocity distribution and airflow pattern profile in different scenarios. The plane section of the velocity and airflow distribution is in the plane z at coordinate -5 m from the wall. The various velocity was conducted at 0.35 m/s, 0.30 m/s, and 0.25 m/s. A HEPA filter filtered out the supply air to ensure clean air coming into the space. A higher velocity could create a more turbulent velocity, increasing when hitting equipment or personnel. Besides that, a higher velocity will also be faster to reach the desired temperature.

Figure **5** depicts the effect of changes in velocity on the temperature in the operating room. The plane section of the temperature distribution results is in the three-dimensional (isometric) view at the height of 1.2 m above the floor according to the field measurement test. The results revealed that all different velocity scenarios could reach the desired temperature of 22°C with a tolerance of ±2°C. The average for each case is 21.45°C, 22.18°C, and 22.85°C, respectively. Figure (**5a**) shows that the greater the velocity is given to the air supply results in the lower temperature and more distribution. In addition, the blue spot area in the center of the room indicates that the area has a lower temperature than other areas because the location of the HEPA is in the center of the ceiling.

3.3. Pressurization

In order to maintain the quality of the air in the operating room, it should have sufficient clean air supplied to dilute and remove the airborne contamination generated within the room. Pressurization is critical to the proper functioning of the cleanroom. So, the contamination can be prevented during the surgery process. Figure **6**. depicts the results of the pressurization in a different scheme. The field measurement was conducted with the

pressurization at 10.6 Pa, compared to the numerical simulation with the pressurization of 10.7 Pa, which is has been validated, and the results are close to the experimental. The design specification of the pressure is 5 Pa, and excessive design air supply creates high pressure. In this study, the face velocity is reduced to find the optimal results. When the existing velocity of 0.35 m/s was decreased to 0.30 m/s and 0.25 m/s resulting in lower pressure, the results are 9.8 Pa and 8.6 Pa, respectively.

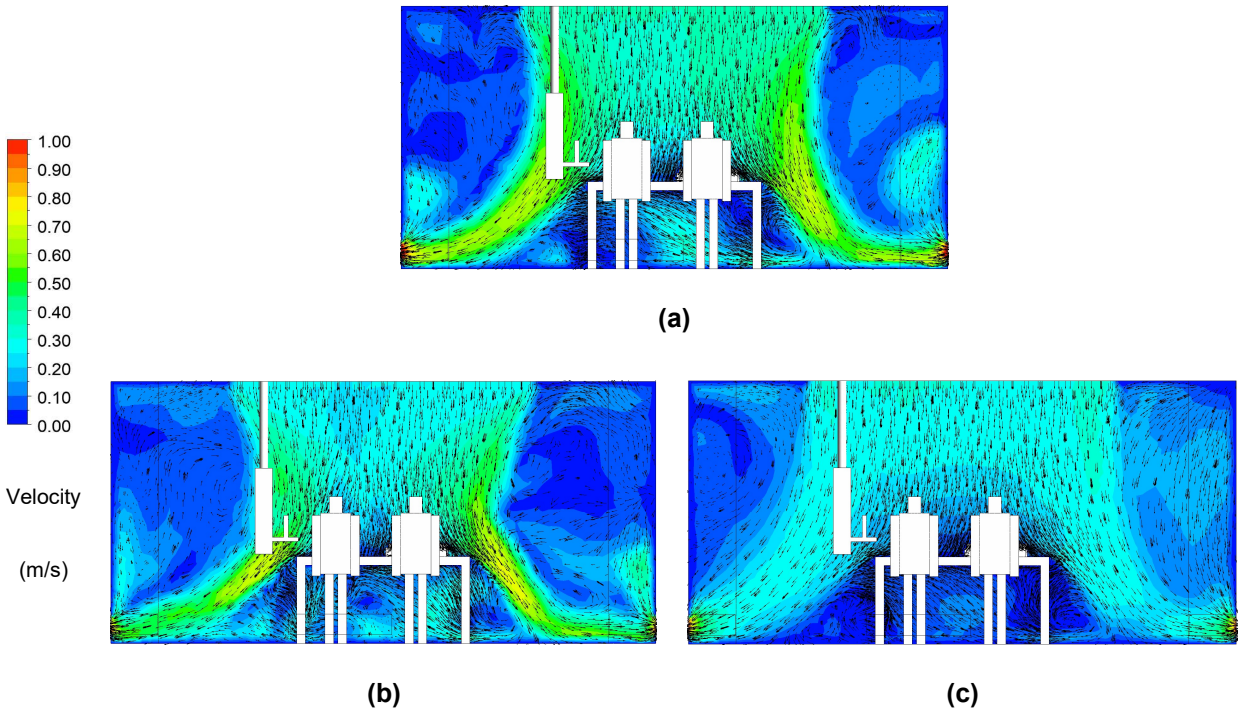

Figure 4: Velocity distribution and airflow pattern profile: (a) v = 0.35 m/s; (b) v = 0.30 m/s; (c) v = 0.25 m/s.

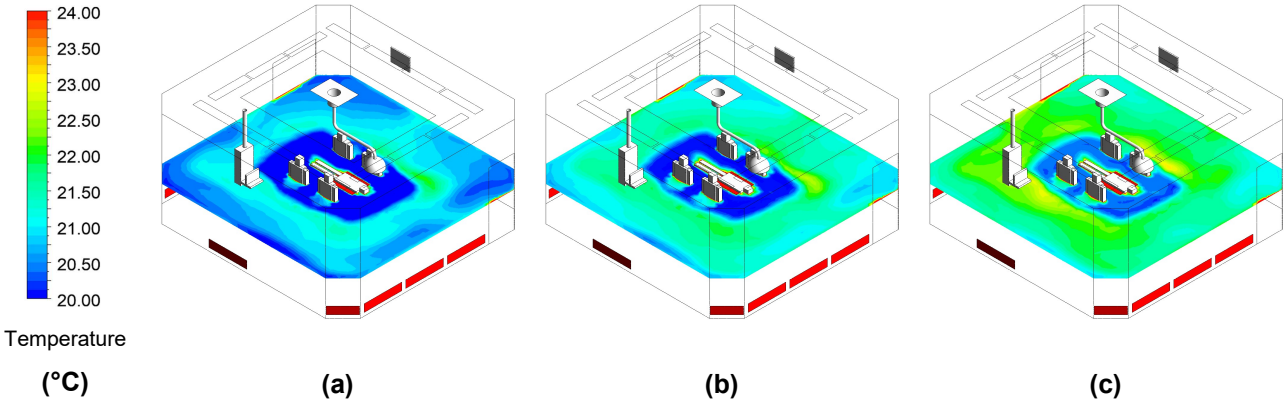

Figure 5: Temperature distribution: (a) v = 0.35 m/s; (b) v = 0.30 m/s; (c) v = 0.25 m/s.

3.4. Concentration Decay Analyses

Contamination control is one of the ways to improve the cleanliness of the operating room. This study aims to prevent bacteria or even fungi from entering the patient's body who is undergoing the surgical process. The concentration decay method was selected and conducted to analyze the effect of different face velocities as a supply air from HEPA. Carbon dioxide (CO_2) was selected as a particle source or contaminant in the operating room. The pathogen as particle source or contaminant is simplified without considering their biological characteristic.

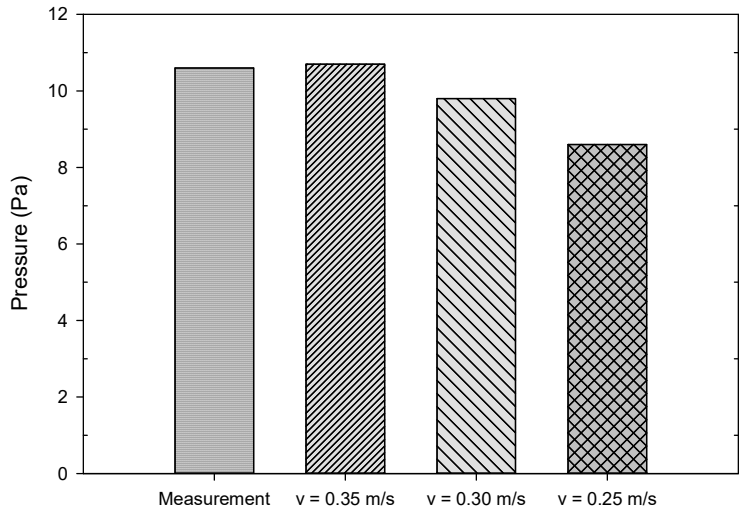

Figure 6: Pressurization results in a different scheme.

The decreasing contaminant concentration was monitor and recorded within 500 seconds, and data collected were retrieved every 25 seconds. The existing velocity of 0.35 m/s results in the lowest concentration in the operating room with a value of concentration at 446 ppm, while the reducing face velocity strategies have a value of concentration at 474 ppm and 495 ppm, respectively. The existing design with a velocity of 0.35 m/s reached the steady-state condition quickly after 300 seconds. The rest of the two designs reached the steady-state condition after 350 seconds and 400 seconds, respectively. The concentration contaminant with face velocity at 0.3 m/s increased 6.2% against the existing velocity design, while by decreasing face velocity to 0.25 m/s, the concentration increased 11.0% against the existing velocity design, which is over the tolerance design by more than 10%. By reducing face velocity or ventilation rate, it could lead to lower energy consumption. However, the contaminant concentration would increase, and also thermal performance would decrease. Therefore, adjusting the optimal ventilation rate should be carried out to meet the needs of thermal performance and contamination control.

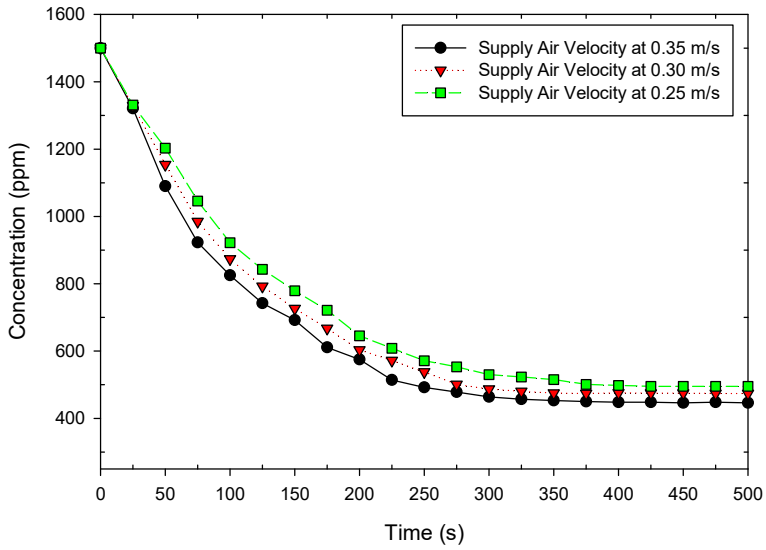

Figure 7: Concentration decay in different face velocity.

4. Conclusion

The study investigated indoor environmental parameters in the operating room through field measurement tests and numerical simulations extensively. The influence of supply air velocity profile has been investigated

numerically to find better approaches to achieve a better design operating room. The following conclusions may be drawn:

- The overall experimental results have been reached the design standard specification. However, there is an over-design ventilation rate that needs to be adjusted to achieve the optimal design.
- The numerical simulation has been validated with the field measurement test extensively with a different number of mesh elements resulting in a lower average error of less than 1% selected.
- Reducing face velocity from the existing design of 0.35 m/s to 0.30 m/s and 0.25 m/s. The overall temperature results have achieved the design specification of 22±2°C. The average for each case is 21.45°C, 22.18°C, and 22.85°C, respectively.
- Reducing the face velocity results in a lower pressure but still achieve the design standard of 5 Pa. The results are 10.6 Pa, 10.7 Pa, 9.8 Pa, and 8.6 Pa, respectively.
- A higher ventilation rate could dilute or remove the contaminant concentration quickly, with the existing design reaching the steady-state condition at 300 seconds, while the others at 350 seconds and 400 seconds. The average at 500 seconds concentration is 446 ppm, 474 ppm, and 495 ppm, respectively.

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