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Numerical Study Of Three-Dimensional Flow In A Negative Pressure Isolation Room With One Inlet And Two Outlets Ventilation Configurations With Variations Bed Positions And Outlets Pressure Differences

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Abstract

Good ventilation planning is required when designing a negative-pressure isolation room. The ventilation system design must ensure proper air circulation throughout the room, with no stagnant air. Furthermore, the inlet and outlet air should not short-circuit. Patient comfort must also be considered, including temperature, velocity, and air pressure. By simulating the room's airflow characteristics, the optimal flow can be determined to maintain low infection levels and patient comfort. A 3D numerical study was conducted on a negative pressure isolation room measuring 6mx8mx3m. The study tested variations in the patient's bed position and outlet pressure -2.5Pa, -5 Pa, -8 Pa, and -15 Pa, respectively. The inlet boundary conditions used a mass flow inlet type with a mass rate of 0.5642 kg/s (12 ACH), and the outlets used a pressure outlet type. The results indicated that an outlet pressure variation of -5 Pa was the best to create a negative pressure room according to standards and maintain patient comfort. One-bed isolation rooms had better airflow characteristics than two-bed isolation rooms, with no air stagnation in the bed area. Patient comfort was maintained with a bed area velocity of less than 0.2 m/s, a temperature below 28°C, and a room pressure not exceeding -1 mmHg or -133 Pa (Gauge Pressure).

Keywords: Negative Pressure Isolation Room, Ventilation Design, Velocity, Temperature, Pressure

1. Introduction

In December 2019, an outbreak of pneumonia linked to severe acute respiratory syndrome (SARS) occurred in Wuhan, China. The disease quickly spread to other cities in China and several other countries. Public health officials in China identified the virus responsible for the outbreak as a new strain that was different from the virus responsible for SARS. On February 12, 2020, the World Health Organization (WHO) officially announced that the disease was caused by a new type of coronavirus, which was named coronavirus disease 2019 (COVID-19) [1].

Patients infected with COVID-19 require treatment in specialized medical facilities that feature negative pressure isolation rooms. Medical facilities are prone to producing relatively high levels of microorganisms, which can adversely affect patients and healthcare workers. Therefore, the design of medical facilities must carefully consider the ventilation system to regulate the level of contaminants and prevent the spread of infections to medical personnel. Proper ventilation planning is essential for designing isolation rooms. The ventilation system must circulate air effectively throughout the room to avoid stagnation and prevent short-circuiting between the inlet and outlet. Additionally, aspects of patient comfort, such as temperature, air velocity, and pressure, must also be considered [2].

Negative pressure isolation rooms, also known as airborne infection isolation rooms, are commonly used for treating patients who are infected or suspected of having an airborne disease. These rooms are designed to reduce the risk of airborne transmission to others. To maintain the negative pressure room, a ventilation system must be provided in the isolation room, and there should be a minimum pressure difference between the isolation room and the surrounding area. According to existing regulations, the minimum pressure difference required between the space and the surrounding area is -2.5 Pa [2, 3].

The ventilation design strategy for isolation rooms should aim to achieve the best use of ventilation while ensuring acceptable patient comfort. The effectiveness of the ventilation system in removing the source of infection and diluting the contaminants is highly dependent on the air mixing process. Proper air mixing helps to improve the dilution and disposal of contaminants. Therefore, it is essential to avoid stagnation and short-circuiting airflow. Patient comfort should also be considered in the ventilation system design, including room temperature, speed,

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and pressure [2]. For instance, the recommended air velocity in a room that passes through the human body is less than 0.2 m/s based on the American standard ASHRAE 55-1992, and the room temperature range for comfort is from 24.9^{o}C to 28^{o}C [4, 5]. Furthermore, the room pressure should approach atmospheric pressure conditions to ensure optimal respiratory function [6].

This investigation aims to use computational fluid dynamics to analyze fluid flow characteristics in a negative pressure isolation room with a ventilation system consisting of one inlet and two outlets. The study will investigate the effects of bed position by varying it between one and two beds, and for each variation, the outlet pressure will be adjusted to values of -2.5 Pa, -5 Pa, -8 Pa, and -15 Pa. The investigation seeks to determine the optimal configuration for airflow in the room. The amount of air circulating in the room is expressed in terms of the air change rate, which compares the volume of air moving through the room to the room volume, and is typically expressed in air change hours (ACH). As specified by regulations, the minimum required air circulation rate is 6 ACH. Critical review regarding theory, performance, practical applications, limitations, and solutions related to ventilation and air distribution methods. While many ventilation methods are buoyancy-driven and only suitable for heating, this review also covers methods appropriate for other modes of operation. In addition, the paper discusses various methods for measuring and evaluating ventilation and air distribution to provide a comprehensive framework for the review [7, 8]. The study employed numerical analysis to enhance the impact of the positioning of air supply and exhaust vents on the fluid flow and temperature distribution in the isolation ward. A model was created for different air supply and exhaust vents arrangements in the isolation room, and simulations were performed using an in-house computational fluid dynamics (CFD) solver [9]. The investigation used CFD to gain insight into the airflow patterns in the isolation room. The study aimed to assess the effectiveness of using conditioned air from air-conditioning units to mix with aerosol sanitizer and ensure it reaches all areas of the room to eliminate the COVID-19 virus. The CFD analysis considered various factors affecting aerosol sanitizer delivery, such as temperature, turbulent kinetic energy, and flow dynamics. To model the laminar-transitional flows numerically, the study employed the transition SST $k-\epsilon$ model, which involves four transport equations. The analysis revealed that generating high turbulent fields inside the isolation room may be an efficient method for distributing sanitizer in a confined space and killing or minimizing the COVID-19 virus [10].

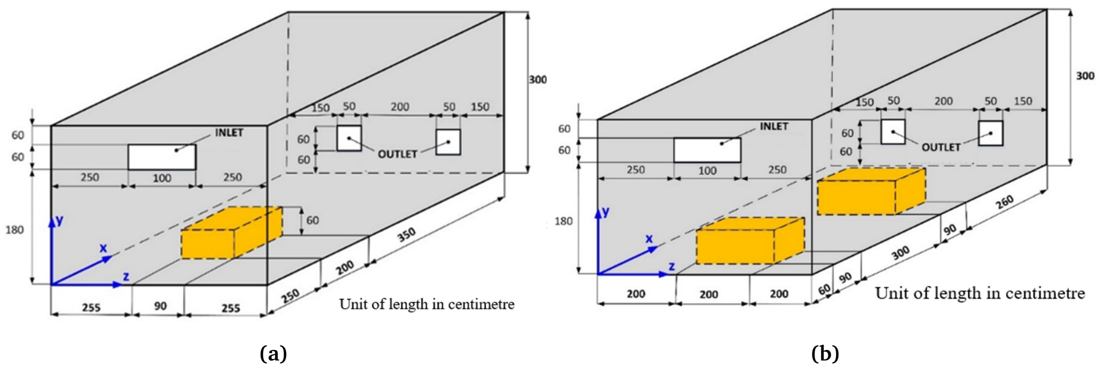


Figure 1. Geometry of the Negative Pressure Insulation Room (a) single bed configuration (b) double bed configuration.

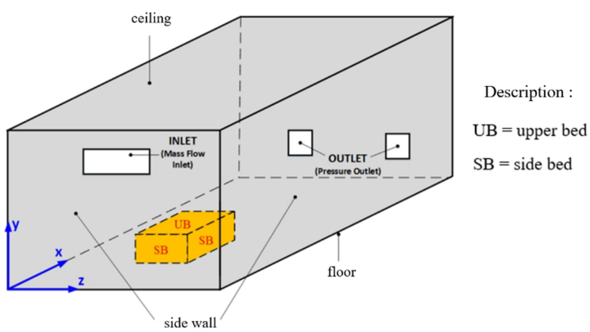


Figure 2. Boundary Conditions of the Negative Pressure Insulation Room.

Table 1. Grid Independence Test

Type	Number of Elements	Velocity at outlets (m/s)	Error (%)
A	762240	0.8571	
B	952800	0.8598	0.313
C	1143360	0.8684	1.001
D	1333920	0.8731	0.545
E	**1524480**	**0.8705**	**0.302**

2. Numerical Method

The geometry of the isolation room is depicted in Figure 1, which was created using Gambit 2.4 software for geometry and mesh generation. A uniform structured hexahedral mesh was employed in this study. Figure 2 displays the boundary conditions of the isolation room, where a mass flow inlet type with a mass rate of 0.5642 kg/s (12 ACH) was used at the inlet and a pressure outlet type at the outlets. The ceiling, side walls, floor, and bed were all assigned a wall-type boundary condition. The study examined the position of the patient's bed and variations in the outlet pressure, including -2.5Pa, -5 Pa, -8 Pa, and -15 Pa, respectively. The upper bed temperature was set at 38.5^{o}C to simplify the patient's body. The turbulence viscous model utilized was k-ϵ standard with the SIMPLE scheme.

Grid independence is used to determine the best level of grid structure to obtain modeling results that are close to the actual conditions. Table 1 shows a grid analysis of the independence of the isolation room model with a variation of one bed. The type of mesh selected is mesh E because it has the most minor error.

This numerical simulation will generate both quantitative and qualitative data. The quantitative data will include the magnitudes of velocity, temperature, and pressure. On the other hand, the qualitative data will comprise of streamline, the contours of velocity, pressure, temperature, and velocity vector.

3. Results and Discussion

3.1. The comparison of streamline between two isolation room configurations

The streamline formed in the isolation room with one bed and two beds is shown in Figures 3 and 4. The variation of outlet pressure creates identical airflow patterns in both room configurations. Both room configurations have similar flow patterns. There is a recirculation flow between the bed and the outlet wall. In addition, there is also a recirculation flow between the bed and the front wall.

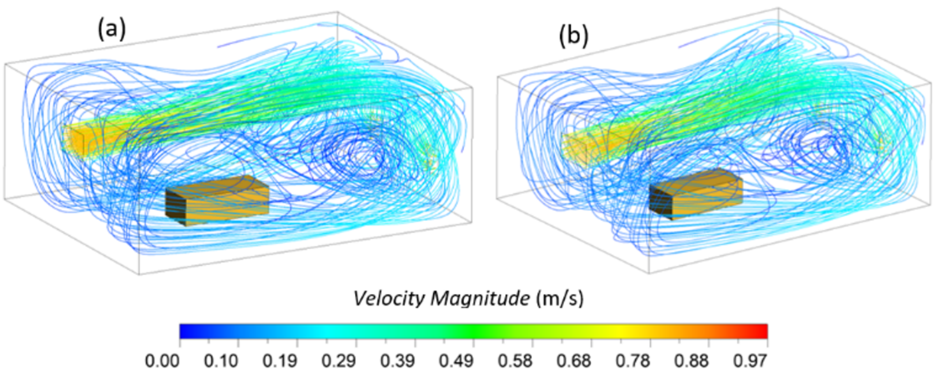


Figure 3. Streamline in single bed isolation room with outlet pressure (a)-2.5 Pa and (b) -15 Pa

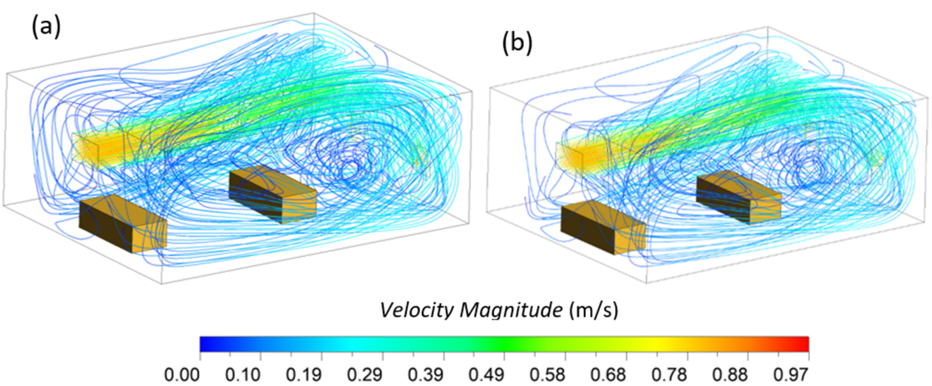


Figure 4. Streamline of double bed isolation room with outlet pressure (a)-2.5 Pa and (b) -15

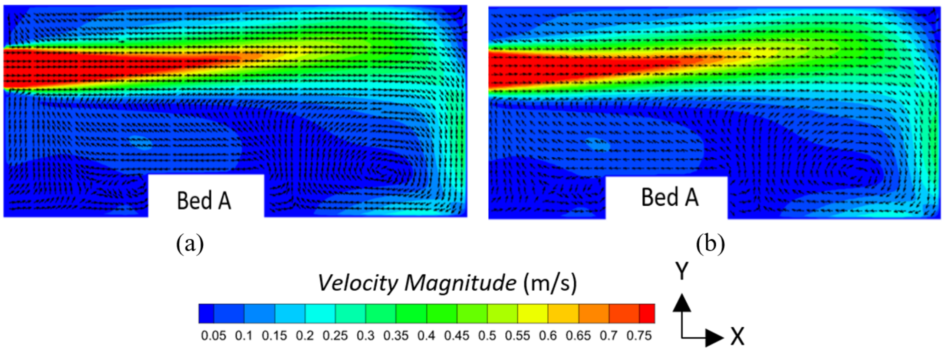


Figure 5. Velocity contour and velocity vector of single-bed isolation room in XY plane (Z = 3m) with outlet pressure (a) -2.5 Pa and (b) -15 Pa

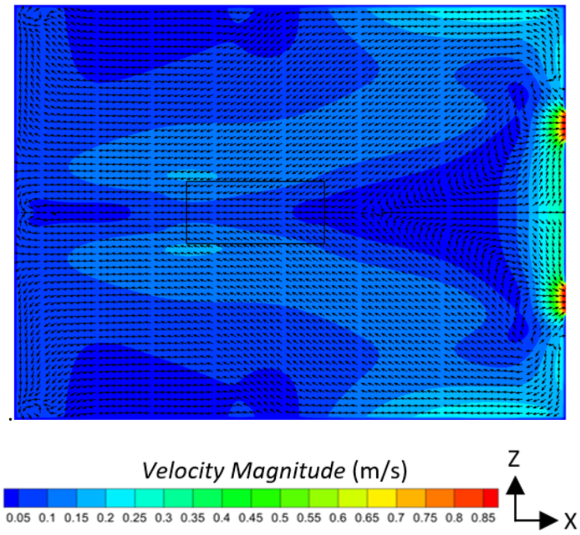


Figure 6. Velocity contour and velocity vector of single bed isolation room in XZ plane (Y = 0,75m) with outlet pressure -2.5 Pa

3.2. Velocity Distribution in Single Bed Isolation Room Configuration

Figure 5 shows if the outlet pressure variations have identical air velocity distributions in the room. The air above the patient is well circulated because it does not stagnate. There is a recirculation flow between the bed and the wall, but the position is far enough from the bed. Recirculation flow should be avoided near the patient bed because it can be a place for the accumulation of pathogenic bacteria. Figure 6 illustrates the velocity vector and velocity contour. The airflow above the bed is well-circulated and does not experience stagnation. The x-y and x-z plane sections also indicate that the airflow in the region above the bed is already optimal.

Figure 7 shows the air velocity value in the x-y plane at a certain height. Each pressure variations have almost the same graph according to the velocity contour. The flow velocity in the bed position, which is between x = 2.5 m to X = 4.5 m at the height of Y = 0.75 m, ranges between 0.036 m/s and 0.0948 m/s. With that velocity value, the patient does not feel a windy condition. So that patient still feels comfort. The air velocity does not exceed the velocity limit of the airflow that hits the patient's body 0.2 m/s based on ASHRAE 55 standard.

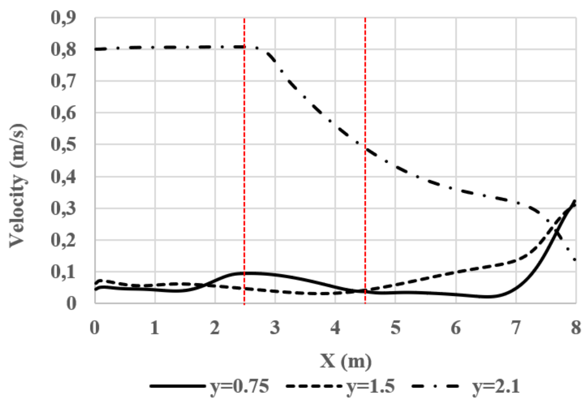


Figure 7. Graph of air velocity in the XY plane (Z=3m) with variations in outlet pressure –2.5 Pa

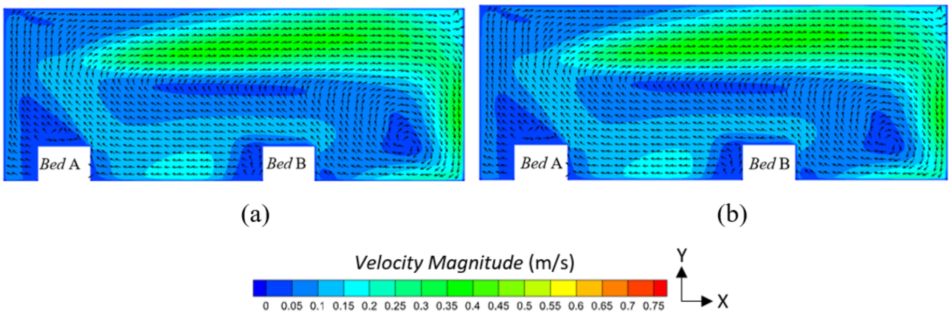


Figure 8. Velocity contour and velocity vector of double bed isolation room in x-y plane (Z = 2,2m) with outlet pressure -2.5 Pa

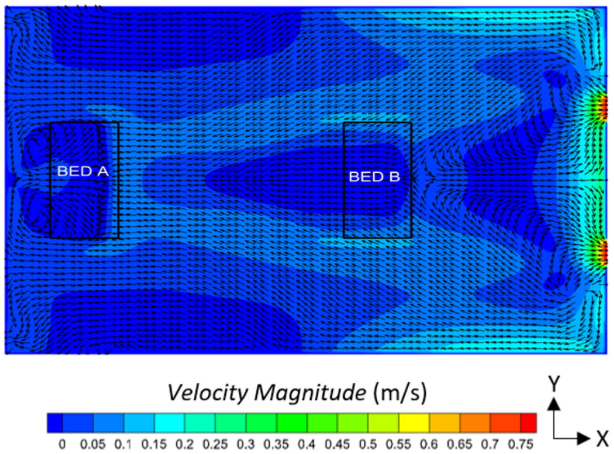


Figure 9. Velocity contour and velocity vector of double bed isolation room in x-z plane (Y = 0,75m) with outlet pressure -2.5 Pa

3.3. Velocity Distribution in Double Bed Isolation Room Configuration

Figure 8 shows if the outlet pressure variations have identical air velocity distributions in the room. There is a recirculation flow between bed B and the wall. The air above bed B is well circulated because it does not stagnate. Whereas in bed A, the air above the bed is not circulated well. The air above bed A flows at a low speed. The low airflow velocity causes the area above bed A occur stagnation.

Figure 9 depicts that the bed A region experiences stagnation flow and recirculation flow, whereas bed B has well-circulated air at the head and feet of the patient but low-speed air in the middle. When comparing the airflow patterns of single and two-bed isolation rooms, single-bed isolation rooms exhibit better airflow as stagnant air occurs above the bed in two-bed isolation rooms along with recirculation flow. At a certain height, Figure 10 illustrates the air velocity values in the x-y plane. The pressure variations almost follow the same graph as the velocity contour. For bed A, the flow velocity ranges from 0.008 m/s to 0.128 m/s between X = 0.6 m and X = 1.5 m at the height of Y = 0.75 m. Although patients don't experience windy conditions, stagnation in this region can lead to bacterial growth due to small particle accumulation. In contrast, for bed B, the flow velocity ranges from 0.082 m/s to 0.132 m/s between X = 4.5 m and X = 5.4 m at the height of Y = 0.75 m, ensuring patient comfort with no feeling of wind. Bed A and B's air velocity does not exceed the ASHRAE standard number 55 of 0.2 m/s for the air flow rate that hits the patient's body. Overall, bed B exhibits better airflow conditions than bed A.

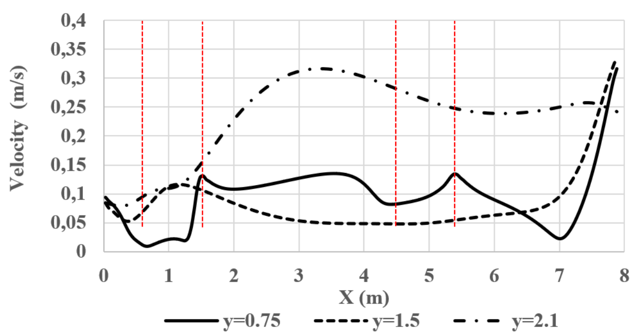


Figure 10. Graph of air velocity in the x-y plane (Z=2,2m) with variation in outlets pressure -2.5 Pa

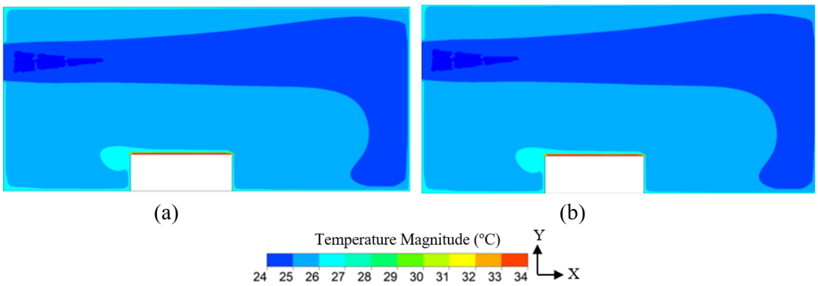


Figure 11. Temperature contour of single bed isolation room in x-y plane (Z = 3 m) with outlet pressure -2.5 Pa

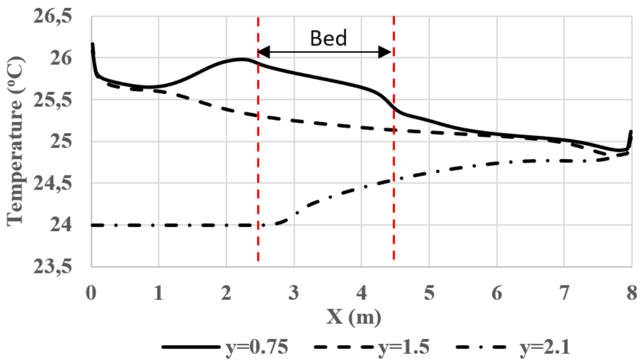


Figure 12. Air temperature distribution in the x-y plane (Z = 3 m) with variations in outlet pressure about –2.5 Pa

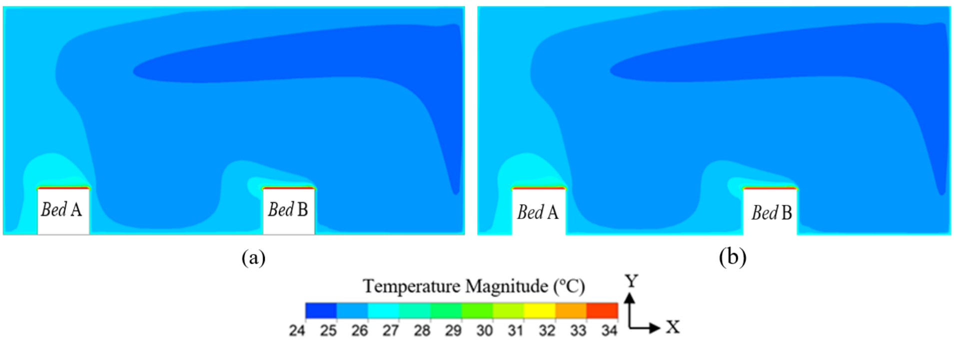


Figure 13. Temperature contour of double bed isolation room in x-y plane (Z = 2,2 m) with outlet pressure -2.5 Pa

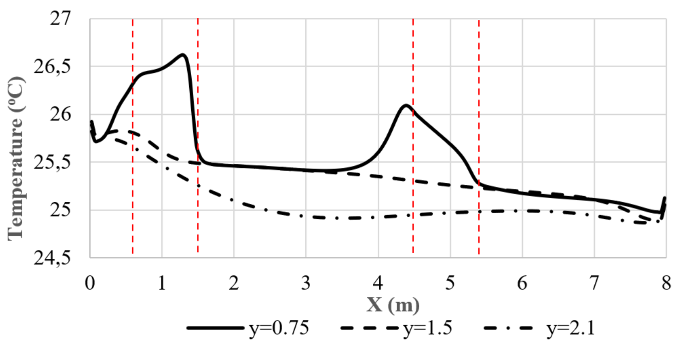


Figure 14. Graph of air temperature in the x-y plane (Z = 2,2 m) with variations in outlet pressure –2.5 Pa

3.4. Temperature Distribution in Single Bed Isolation Room Configuration

Figure 11 shows if the outlet pressure variations produce identical temperature distributions in the room. The air that comes out through the inlet has a lower temperature than the air in the room. The air has a high temperature above bed A because the upper surface bed has a high temperature representing the presence of a fever patient.

Figure 12 shows the air temperature value in the bed position, which is between X = 2.5 m to X = 4.5 m at the height of Y = 0.75, with a value ranging between 25.36^{o}C and 25.92^{o}C. The range of temperature values does not make the patient feel hot conditions. So that patient still feels comfortable. The temperature is still within the range of thermal comfort for Indonesians because the value is not more than 28^{o}C.

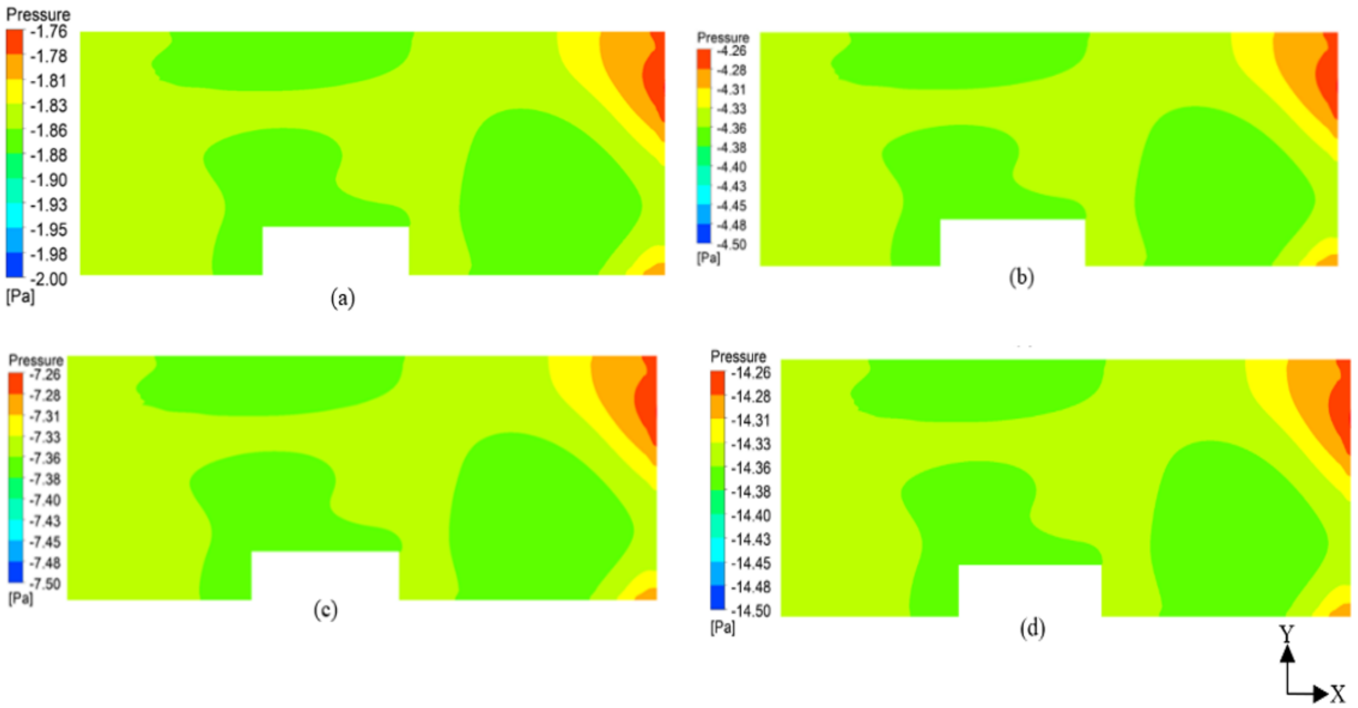


Figure 15. Pressure contour of single bed isolation room in x-y plane (Z = 3 m) with outlet pressure -2.5 Pa

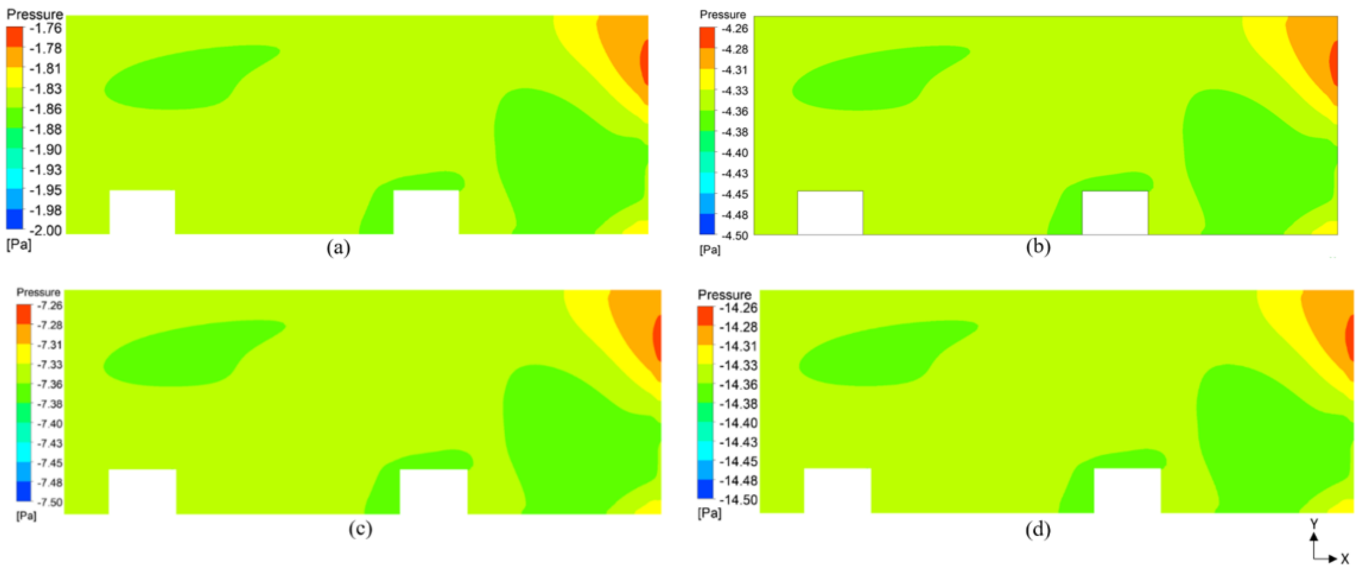
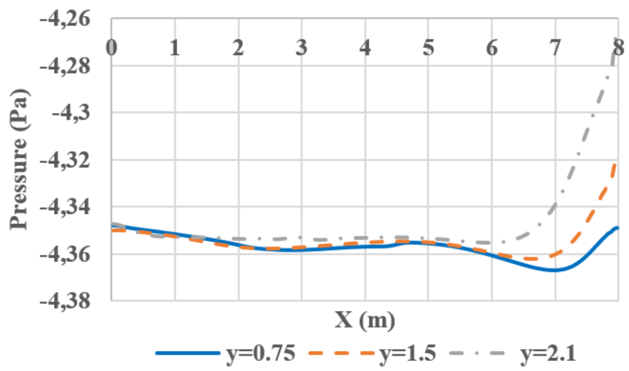
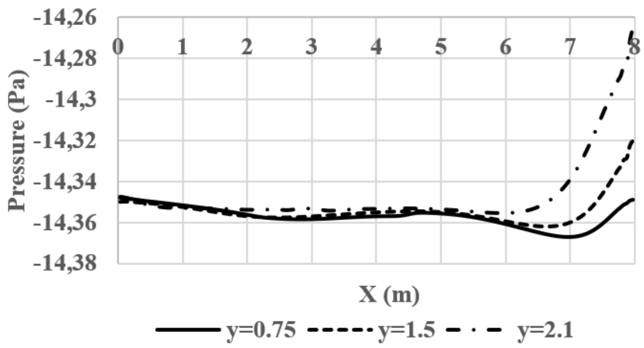


Figure 16. Pressure contour of double bed isolation room in x-y plane (Z = 2,2 m) with outlet pressure -2.5 Pa

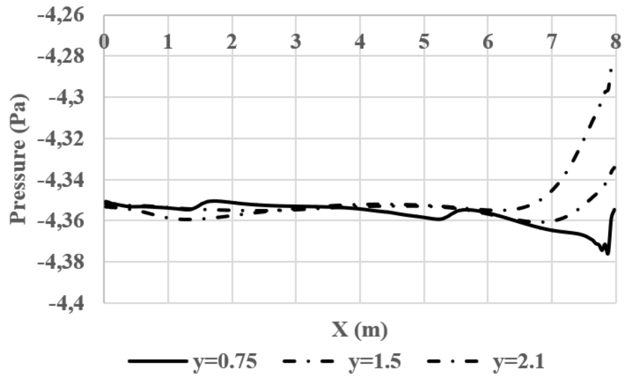


(a) -5 Pa

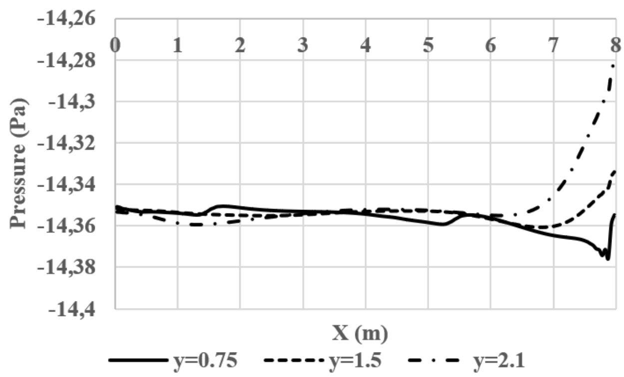


(b) -15 Pa

Figure 17. Graph of air pressure in the x-y plane (Z = 3 m) with variations in outlet pressure (a) -5 Pa dan (b) -15 Pa



(a) -15 Pa



(b) -15 Pa

Figure 18. Graph of air pressure in the x-y plane (Z = 2,2 m) with variations in outlet pressure (a) -5 Pa dan (b) -15 Pa

3.5. Temperature Distribution in Double Bed Isolation Room Configuration

Figure 13 depicts that the variations in outlet pressure result in uniform temperature distribution throughout the room. The temperature contour reveals that the bed area exhibits a higher temperature than other areas due to heat transfer between the bed and air. The temperature at the top of the room is lower than the bottom because the air coming out is cooler than the room air. Bed A's surrounding air has a higher temperature than bed B's because of flow stagnation, which results in lower heat transfer from the bed to the air.

In Figure 14, the air temperature at bed A between X = 0.6 m to X = 1.5 m at the height of Y = 0.75 m ranges between 25.67oC and 26.61^{o}C. Bed B's air temperature between X = 4.5 to X = 5.4 m at the height of Y = 0.75 m ranges from 25.24^{o}C to 26^{o}C. The patient would feel comfortable with this temperature because they would not experience hot air. The temperature falls within the thermal comfort range for Indonesians since it is below 28^{o}C.

3.6. Pressure Distribution in Single Bed Isolation Room and Double Bed Isolation Room

Both Figures 15 and 16 show similar spatial pressure distributions for variations in outlet pressure, albeit with different pressure values. The pressure contour indicates that the pressure in the bed area is not significantly different from other areas. However, a -2.5 Pa outlet pressure variation in both room configurations does not comply with pressure regulations, as some areas in the room fail to achieve the minimum pressure difference of -2.5 Pa. A pressure difference of -5 Pa is the most suitable as it meets regulations and does not cause breathing difficulties for patients during inspiration. During inspiration, the alveolar pressure in the lungs becomes -1 mmHg or -133.32 Pa. Hence, the more negative the room pressure, the more difficult it becomes for the patient to breathe. Figures 17 and 18 show that the pressure variation graphs exhibit the same trend line for each bed configuration. The air pressure at heights of Y = 2.1 m, Y = 1.5 m, and Y = 0.75 m follows the same trend line for each pressure variation. The difference between the smallest and largest pressure values is not significantly different for each pressure variation.

3.7. Conclusions

Based on the post-processing of numerical simulation results, the research yielded several conclusions, as follows:

1. The variation of outlet pressure of -5 Pa is optimal because it creates a negative pressure room that meets standards while maintaining patient comfort by not making the room pressure too negative.
2. The isolation room with a single bed has better airflow characteristics than a double bed because there is no air stagnation or recirculation flow above the bed. To eliminate the issues in the double bed isolation room, one of the beds can be shifted 1.6 m from the wall while leaving the other bed in a fixed position.
3. In the single-bed isolation room, the air velocity around the bed is below the comfortable limit of 0.2 m/s, with a maximum of 0.154 m/s, and the maximum air temperature in that area is 25.92^{o}C, which is also below the comfortable temperature limit of 28^{o}C. Room pressures ranging from -2.5 Pa to -15 Pa are considered safe because they fall below the vacuum pressure of lung alveoli during inspiration.
4. In the double bed isolation room, the air velocity around Bed A is below the comfortable limit of 0.2 m/s, with a maximum of 0.128 m/s, and the maximum air temperature is 26.61^{o}C, below the comfortable temperature limit of 28^{o}C. The air velocity around Bed B is below the comfortable limit of 0.2 m/s, with a maximum of 0.156 m/s, and the maximum air temperature is 26^{o}C, which is also below the comfortable temperature limit of 28^{o}C. Room pressures ranging from -2.5 Pa to -15 Pa are considered safe because they fall below the vacuum pressure of lung alveoli during inspiration.

References

[1] Z. Y. Zu, M. D. Jiang, P. P. Xu, W. Chen, Q. Q. Ni, G. M. Lu, and L. J. Zhang, "Coronavirus disease 2019 (covid-19): a perspective from china," *Radiology*, vol. 296, no. 2, pp. E15–E25, 2020.

[2] I. C. S. F. J. C. N. T. Center, *Isolation Rooms: Design, Assessment, and Upgrade*. Francis J. Curry National Tuberculosis Center, Institutional Consultation Services, 1999.

[3] TAHPI, *International Health Facilities Guidelines Part D – Infection Control*. TAHPI, 2017.

[4] A. Standard, "Thermal environmental conditions for human occupancy," *ANSI/ASHRAE, 55*, vol. 5, 1992.

[5] T. H. Karyono, "Penelitian kenyamanan termis di jakarta sebagai acuan suhu nyaman manusia indonesia," *DIMENSI (Journal of Architecture and Built Environment)*, vol. 29, no. 1, pp. 24–33, 2001.

[6] G. Mols, B. von Ungern-Sternberg, E. Rohr, C. Haberthür, K. Geiger, and J. Guttmann, "Respiratory comfort and breathing pattern during volume proportional assist ventilation and pressure support ventilation: a study on volunteers with artificially reduced compliance," *Critical care medicine*, vol. 28, no. 6, pp. 1940–1946, 2000.

[7] B. Yang, A. Melikov, A. Kabanshi, C. Zhang, F. Bauman, G. Cao, H. Awbi, H. Wigö, J. Niu, K. Cheong, K. Tham, M. Sandberg, P. Nielsen, R. Kosonen, R. Yao, S. Kato, S. Sekhar, S. Schiavon, T. Karimipanah, X. Li, and Z. Lin, "A review of advanced air distribution methods - theory, practice, limitations and solutions," *Energy and Buildings*, vol. 202, p. 109359, 2019.

[8] G. Cao, H. Awbi, R. Yao, Y. Fan, K. Sirén, R. Kosonen, and J. J. Zhang, "A review of the performance of different ventilation and airflow distribution systems in buildings," *Building and Environment*, vol. 73, pp. 171–186, 2014.

[9] S. Jacob, S. S. Yadav, and B. S. Sikarwar, "Design and simulation of isolation room for a hospital," in *Advances in Fluid and Thermal Engineering: Select Proceedings of FLAME 2018*, pp. 75–93, Springer, 2019.

[10] S. Bhattacharyya, K. Dey, A. R. Paul, and R. Biswas, "A novel cfd analysis to minimize the spread of covid-19 virus in hospital isolation room," *Chaos, Solitons and Fractals*, vol. 139, p. 110294, 2020.