JMES The International Journal of
Mechanical Engineering and Sciences
https://iptek.its.ac.id/index.php/jmes
e-ISSN 2580-7471

Numerical Study of Three-Dimensional Flow Characteristics in Isolation Rooms with Negative Pressure Differences

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Received: 1 September 2021, Revised: 3 September 2023, Accepted: 3 September 2023

Abstract

This paper will discuss computational fluid dynamics (CFD) modeling regarding a patient isolation room design with negative pressure. This model was made after conducting independence tests and validation data on several existing room designs. The room design is simulated with variations in pressure differences -2.5 Pa, -5 Pa, -8 Pa, and -15 Pa, respectively, and variations in the position of one bed and two beds. The results show that a lot of stagnation flow occurs in the isolation room with a two-bed configuration and in a more dangerous position than the stagnation flow in the one-bed configuration. The greater the pressure difference used, the more uniform the pressure in the room. The conclusion is that the distribution of pressure difference variations has the same trend on the velocity and temperature distribution graph, then the pressure difference variation of -15 Pa has the best pressure distribution. Variations in bed position configuration affect the characteristics of airflow in the room. The velocity, pressure, and temperature along the bed are still within the patient's comfort limit.

Keywords: Negative pressure room, simulation, ventilation

1. Introduction

The outbreak of pneumonia associated with the new coronavirus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was reported in Wuhan, Hubei Province, China, in December 2019. Researchers from China said the outbreak in Wuhan was caused by a new coronavirus known as 2019-nCoV. Two weeks after the virus was discovered, WHO declared the disease caused by SARS-CoV-2, referred to as COVID-19, and designated it a pandemic. Transmission of the SARS-CoV-2 virus can occur in the form of droplets produced when sneezing, coughing, or in the air (airborne).

One of the preventive measures to reduce fatalities is to reduce the rate of transmission of the SARS-CoV-2 virus. Patients exposed to COVID-19 must be isolated to prevent transmission to others. An isolation room is designed to ensure protection from all methods of infection transmission. The most dominant mode of infection is airborne transmission which is handled by appropriate heating, ventilation, and cooling (HVAC) systems. There are two classes of isolation rooms, namely class N, which has negative pressure, and class P, which has positive pressure. The isolation room with negative pressure is suitable for patients suffering from infectious diseases such as Tuberculosis and SARS.

Therefore, to design a negative pressure isolation room, it is necessary to design good ventilation to circulate the air in the room. Some parameters that need to be considered to design good ventilation are the room's velocity distribution, temperature, and pressure. A numerical simulation is one method that can predict the flow pattern in a negative pressure isolation room.

In this study, a numerical study was conducted to determine the phenomena that occur in an isolation room with variations in pressure differences of -2.5, -5, -8, and -15 Pa, respectively, and variations in bed positions, namely, one bed and two beds. The distribution of temperature, pressure, and velocity in a negative pressure room can provide information about air circulation in a negative pressure room.

2. Previous Research Description

2.1. Isolation Room Classification

Rooms in a health facility require different pressures than the other rooms. Isolation rooms can be divided into several classifications, namely Class S (Standard Pressure) is an isolation room for patients who can infect through contact or droplets. Class N (Negative Pressure) is an isolation room for patients who can infect through the air. Class P (Positive Pressure) is an isolation room for immunocompromised patients who cannot be directly exposed to outside air. [1]

Negative pressure rooms are suitable for patients with diseases that can infect through the air because exhaust ventilation in negative pressure rooms forces the air

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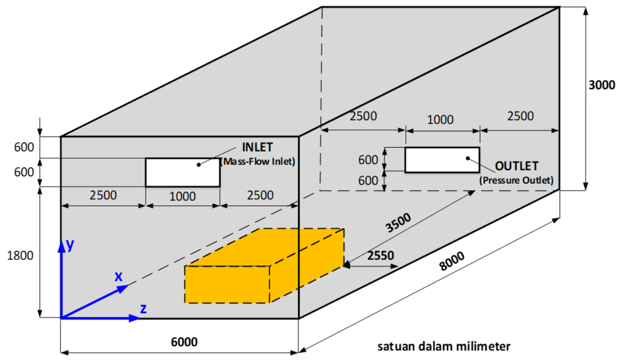
out of the room. Each country has its policy regarding the recommended pressure difference used. For example, the United States recommends -2.5 Pa [2], and Australia recommends a minimum of -15 Pa. [1]

2.2. Ventilation Rate

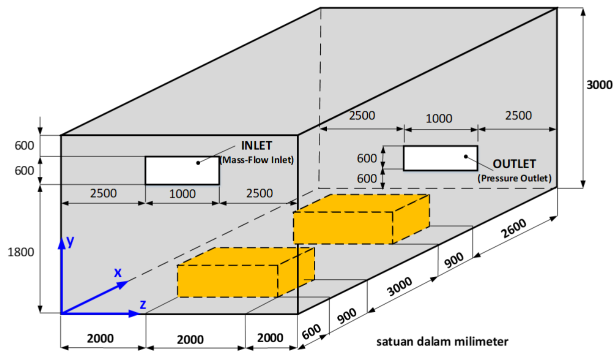
The change of entering and leaving air is vital in a health facility. The volume of air changes can be measured in units of Air Changes per Hour (ACH). ACH is a measurement of the volume of air entering and leaving in one hour divided by the volume of the room. [3] Each country has its policy regarding air change rates, such as the United States, at least 12 ACH, and WHO recommends 6-12 ACH.

2.3. Previous Room Design

A numerical study of the flow phenomena in the patient isolation room with room dimensions of 4.88 m x 3.60 m x 3.05 m with a ventilation rate variation of 12 ACH and five variations was carried out. [4] It was concluded that the design of a room with the patient located close to the inlet or air supply is highly recommended for immunosuppressed patients. Room design with a multidirectional flow can be a good solution for patients infected with disease because it offers better control of ventilation parameters by multiple inlet ventilation.



(a) One bed



(b) Two beds

Figure 1. Schematic diagram of the isolation room with (a) one bed and (b) two beds

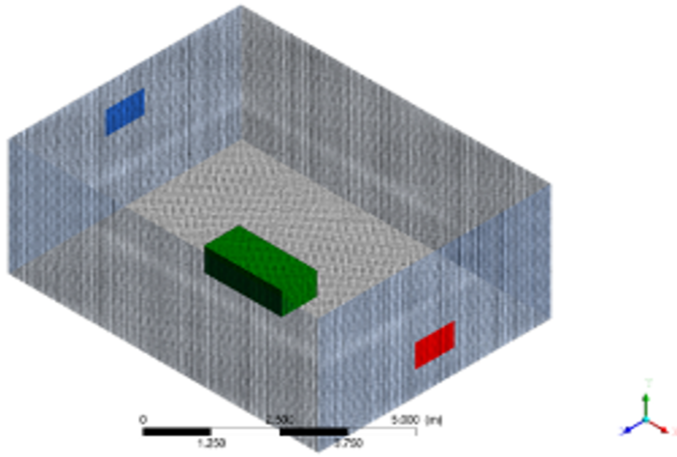


Figure 2. Structured mesh with hexahedral-map type

An experimental study was conducted to discuss the effect of pressure differences and the mobility of health workers on the effectiveness of the patient isolation room. [5] This study was carried out by releasing microparticles of fluorescents to determine the spread of disease-causing particles. The variation used is the difference in room pressure of -2.5, -11, and -20 Pa, respectively, and variations in the mobility of health workers who leave and enter the room. In this study, the results showed that at a pressure difference of -20 Pa, fewer particles came out of the room than the condition of the room with a pressure difference of -2.5 Pa. Variations in labor mobility affect the number of particles leaving the room. The more frequent the mobility of health workers, the greater the possibility of particles leaving the room.

3. Numeric Scheme and Methods

3.1. Geometry Object and Meshing

The simulation domain is built from the room adaptation conducted by Jacob et al. The isolation room used has a dimension of 8 m × 6 m × 3 m with inlet and outlet dimensions of 1 m × 0.6 m. Figure 1 shows a schematic diagram of the isolation room.

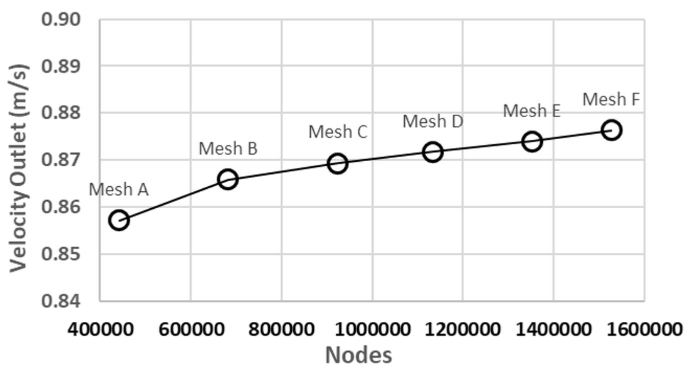
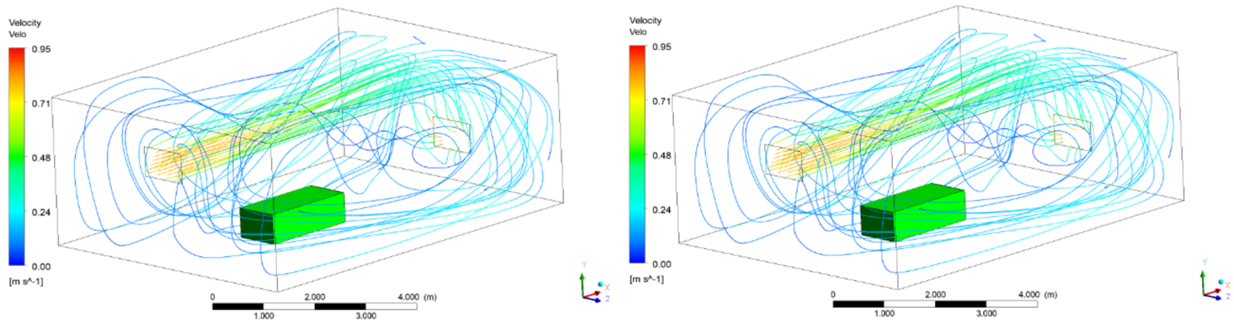


Figure 3. Grid independency test are related with velocity oulet



(a) One bed

(b) Two beds

Figure 4. Velocity pathline in an isolation room with (a) one bed and (b) two beds

The meshing used is a structured mesh with a hexahedral-map type created on Gambit software, shown in Figure 2.

3.2. Boundary Condition

The boundary conditions used are mass-flow inlet of 0.564 kg/s with pressure-outlet variations of -2.5 Pa, -5 Pa, -8 Pa, and -15 Pa, respectively. The fluid used is air at a temperature of 24^{o}C at a pressure of 1 atm. The upper side of the bed is assumed to be a simplified patient with a constant temperature of 38.5^{o}C. The turbulence viscous model is applied k-ϵ standard with the SIMPLE scheme.

3.3. Grid Independence Test

The grid independence test aims to determine the best and most efficient grid structure level so that the modeling results are close to the actual phenomenon. Figure 3 shows a grid graph of independence against velocity at the room's outlet. Mesh E was chosen because the number of meshes is less than Mesh F, but the difference in speed values is the same.

4. Data Analysis and Discussion

4.1. Velocity Pathline

Figure 4 shows the velocity path line of the airflow in the room. The velocity path line indicates a circulating flow between the bed and the outlet caused by the flow that does not come out through the outlet. The flow that hits the room floor changes direction towards the bed and then towards the flow from the inlet so that the flow continues circulating.

4.2. Velocity contour and streamline of flow in a single-bed isolation room

The distribution of fluid flow velocity can be seen through the velocity contour. Figure 5 shows the velocity contour with a streamline of the fluid flow in the x-y plane (z=3), where the streamline indicates the presence of vortices near the bed. This vortex can be a place for bacteria or disease viruses to collect, so the vortex should not occur near the bed.

Figure 6 shows the velocity contour with a streamline in a single-bed isolation room on the z-y plane (x=4). The picture shows a vortex that occurs in the middle of the room, but the flow position is still safe because it is quite far from the bed position.

4.3. Velocity and streamline of flow in a two-bed isolation room

Figure 7 shows the vortex that occurs in both beds. One of the vortices occurs just above the bed near the inlet. The position of this flow is dangerous because bacteria or disease viruses that accumulate in the flow can aggravate the patient or infect the health workers who treat the patient.

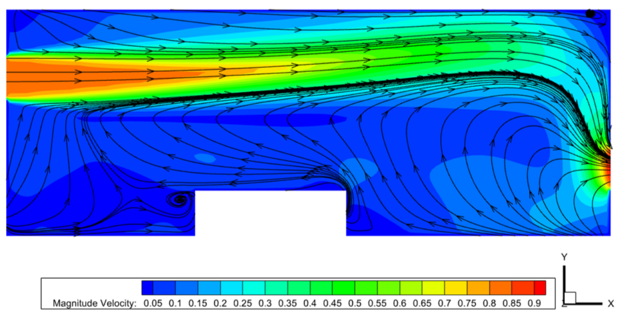


Figure 5. The contour of air velocity and streamline in a single bed isolation room in the x-y plane (z=3)

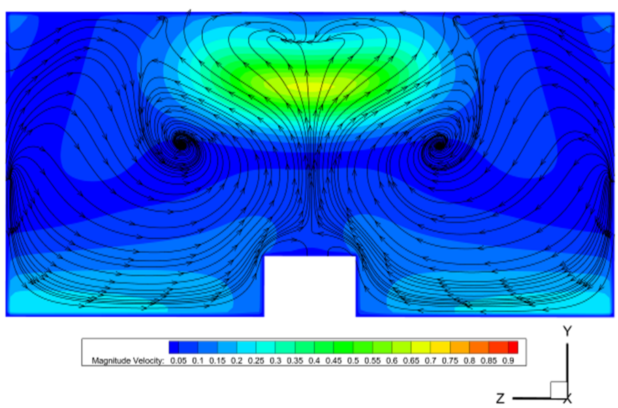


Figure 6. The contour of air velocity and streamline in a single bed isolation room in the z-y plane (x=4)

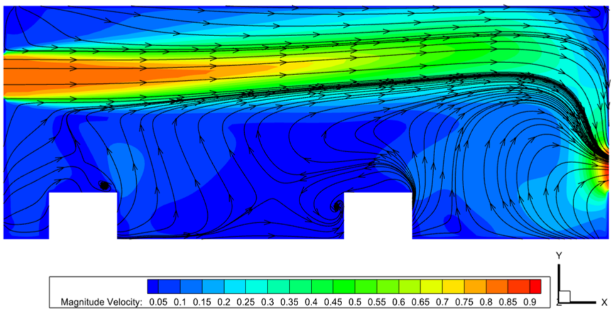


Figure 7. The contour of air velocity and streamline in a two-bed isolation room in the x-y plane (z=3)

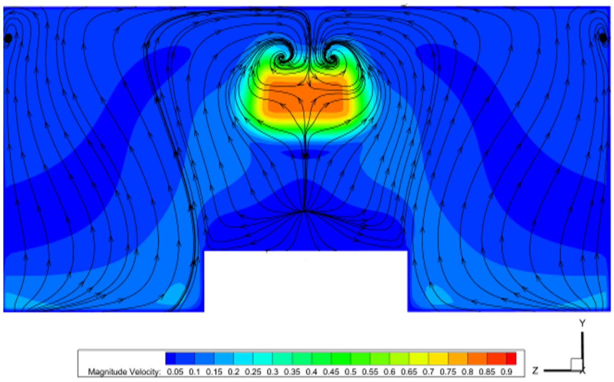


Figure 8. The contour of air velocity and streamline in a two-beds isolation room in the z-y plane (x=1.05)

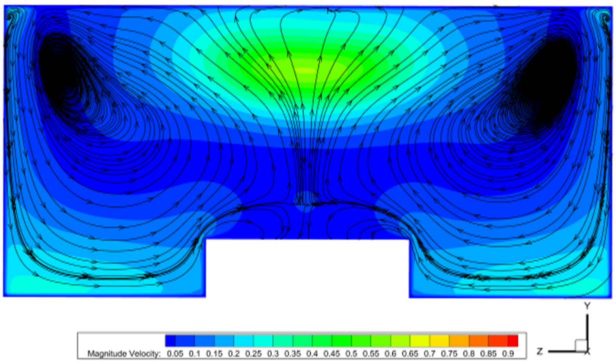


Figure 9. The contour of air velocity and streamline in a two-beds isolation room in the z-y plane (x=4.95)

Figure 8 shows the velocity and streamline contours in the two-bed isolation room in the z-y plane (x=1.05) or parallel to the bed near the inlet. The figure shows the vortex near the inlet. This vortex flow is still safe because it occurs in a position far from the bed.

Figure 9 shows the velocity and streamline contours in the two-bed isolation room in the z-y plane (x=4.95) or parallel to the bed near the outlet. The picture shows that there is a fairly large vortex in the room, but still far from the bed.

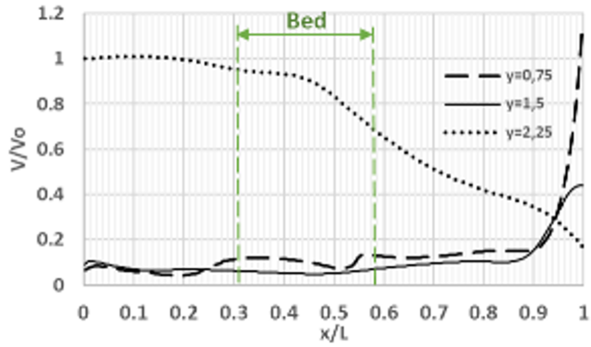


Figure 10. Graph of flow velocity distribution in a single bed isolation room in the x-y plane (z=3)

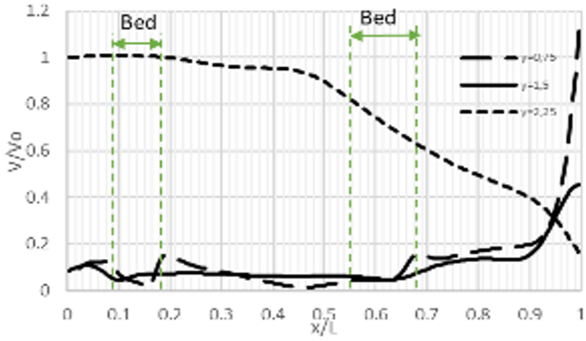


Figure 11. Graph of flow velocity distribution in a two-beds isolation room in the x-y plane (z=3)

4.4. Velocity Distribution Comparison

Quantitative data also represents the flow velocity in the room in the form of a velocity distribution graph. Figure 10 shows a chart of the flow velocity distribution in a single-bed isolation room. Figure 11 shows a chart of the flow velocity distribution in a two-bed isolation room. In comparing the two charts, it can be seen that the line y=0.75 shows a different line because the room height of y=0.75 is the height parallel to the patient, and the graph is affected by bed position. The average speed in the area around the bed is still below 0.2 m/s, so it is still considered safe.

4.5. Flow vector in a-single bed isolation room

In Figure 12, it is shown that the flow vector that occurs in the single-bed isolation room is the occurrence of vortex flow near the bed at a fairly low speed and circulation flow near the outlet.

4.6. Flow vector in a two-bed isolation room

Figure 13 shows the flow vector that occurs in the two-bed isolation room, namely the occurrence of vortices in both beds. The figure shows a vortex flow just above the bed near the inlet, which is dangerous for patients and healthcare workers.

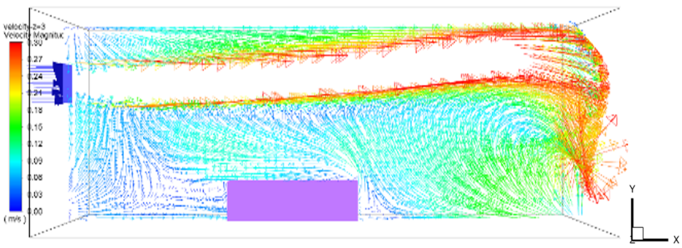


Figure 12. The flow vector in the one bed isolation room in the x-y plane (z=3)

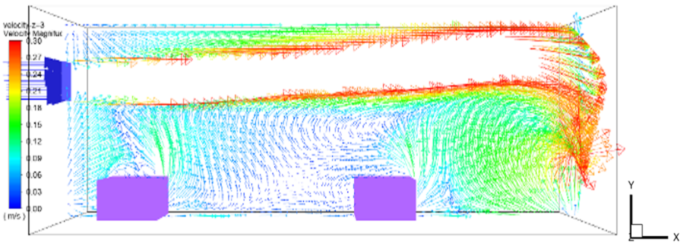
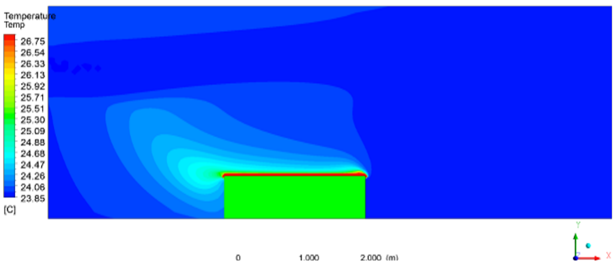
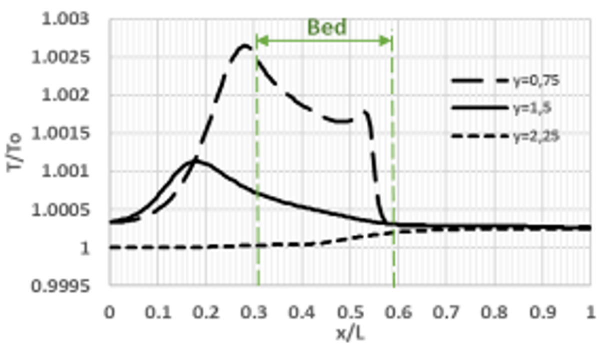


Figure 13. The flow vector in the two-beds isolation room in the x-y plane (z=3)



(a)



(b)

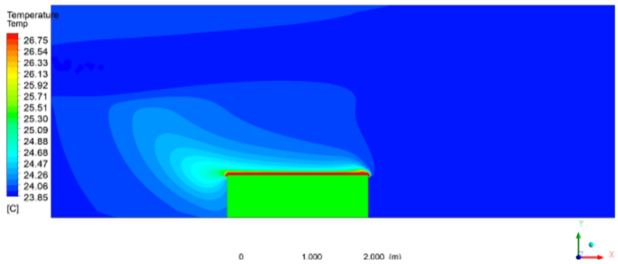
Figure 14. (a) The temperature contour and (b) the temperature distribution graph in the single-bed isolation room

4.7. Temperature distribution in a single-bed isolation room

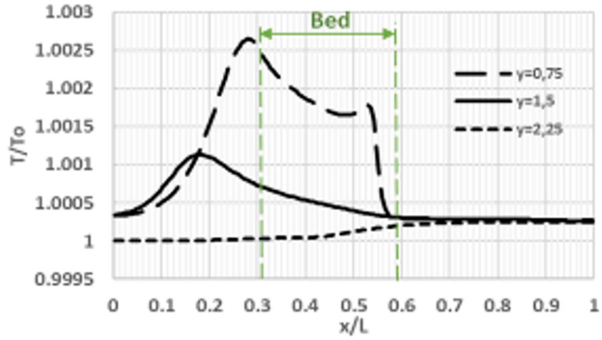
Figure 14 shows the temperature contours and charts of the temperature distribution in a single-bed isolation room where there is a temperature distribution towards the inlet due to forced convection of the heat generated by the patient being pushed by the flow of air towards the inlet.

4.8. Temperature distribution in a two-bed isolation room

Figure 15 shows the contours and graphs of the temperature distribution in the two-bed isolation room where there is a temperature distribution to the inlet caused by forced convection of the airflow to the inlet.

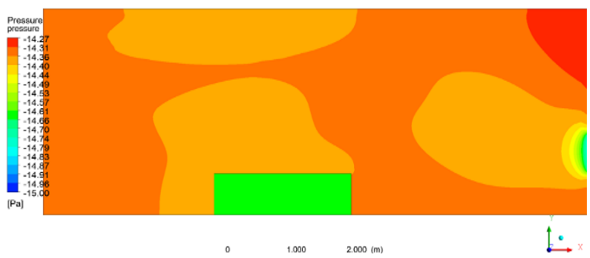


(a)

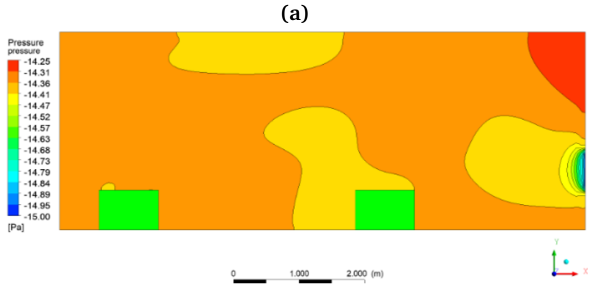


(b)

Figure 15. (a) The temperature contour and (b) the temperature distribution graph in the two-beds isolation room



(a)



(b)

Figure 16. Pressure distribution in (a) single-bed isolation room and (b) two-bed isolation room

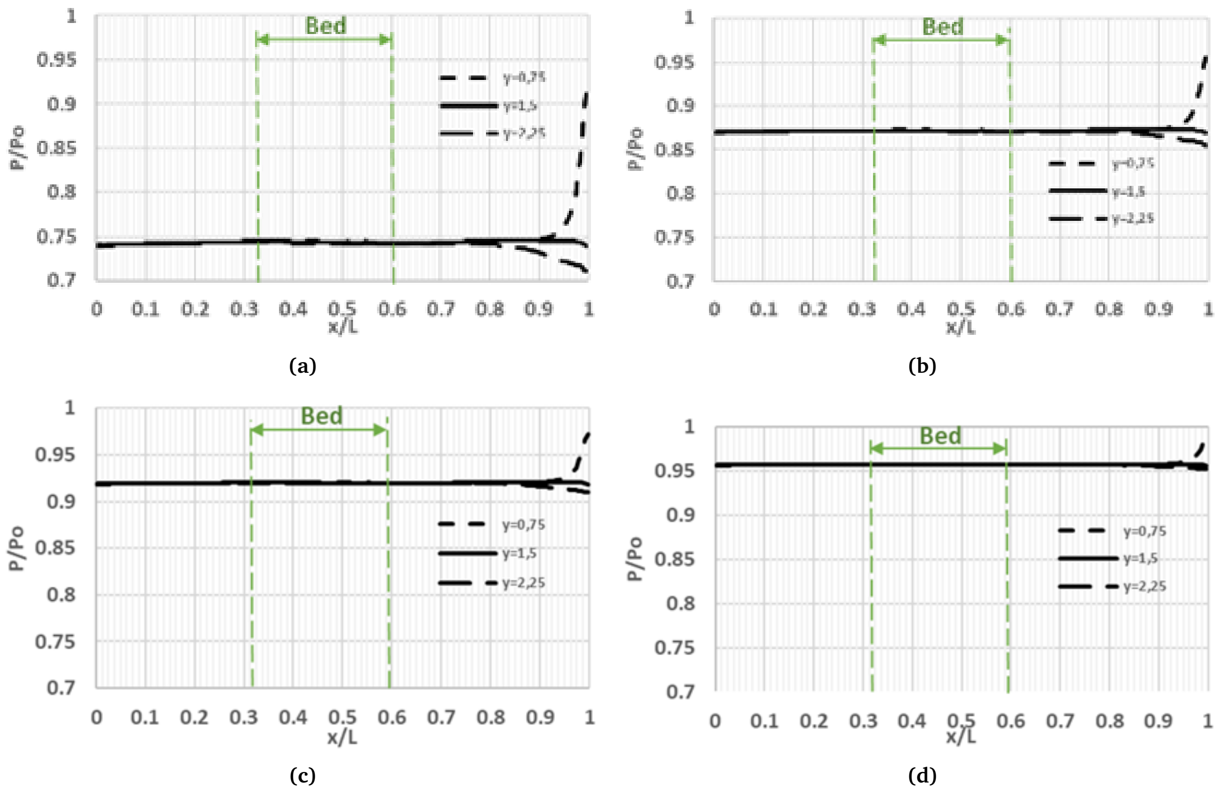


Figure 17. Graph of pressure distribution in a single-bed isolation room with variations of (a) -2.5 Pa, (b) -5 Pa, (c) -8 Pa, and (d) -15 Pa

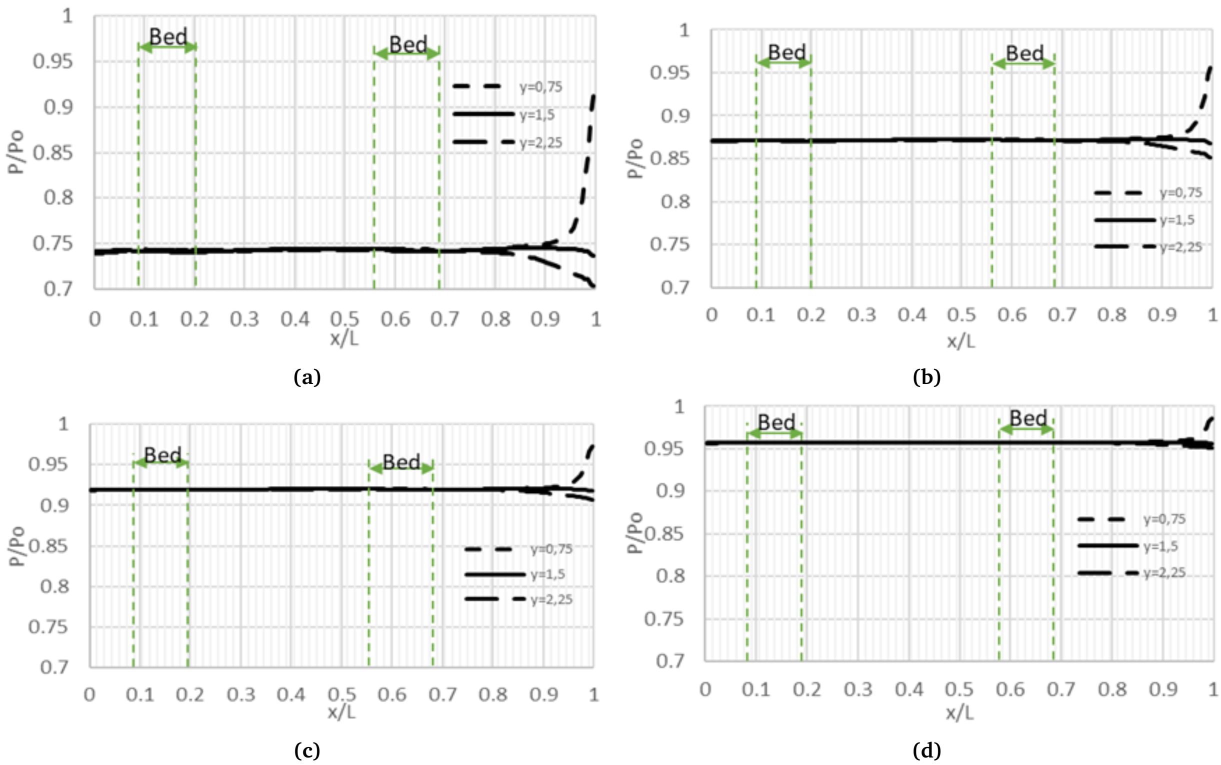


Figure 18. Graph of pressure distribution in a single-bed isolation room with variations of (a) -2.5 Pa, (b) -5 Pa, (c) -8 Pa, and (d) -15 Pa

4.9. Pressure distribution in the isolation room

Figure 16 shows the pressure distribution in one-bed and two-bed isolation rooms. The comparison of contours shows that the bed area has a pressure difference that is not too significant than the surrounding pressure. The vacuum pressure generated when humans do inspiration is -1 mmHg or -133 Pa. [6] The vacuum pressure in the bed area is still within safe limits of the lung vacuum pressure when the patient breathes so that the patient is still comfortable breathing.

4.10. Graph of pressure distribution in a single bed isolation room with pressure differences variations

Figure 17 shows a graph of the pressure distribution in a two-bed isolation room where the variation of -2.5 Pa the pressure that occurs in the room is only 75% from -2.5 Pa, while at the variation of -15 Pa, the pressure distribution that occurs in the room is more uniform and closer to the value. The pressure at the outlet is 95% of -15 Pa. The average pressure along the bed is still more positive than the pulmonary pressure, which is -133 Pa, so the patient is still comfortable.

4.11. Graph of pressure distribution in the two-bed isolation room with pressure differences variations

Figure 18 shows a graph of the pressure distribution in a two-bed isolation room. The distribution of pressure that occurs has the same trend where the variation of -2.5 Pa, the pressure distribution that occurs in the room is only 75% from -2.5 Pa, while at the variation of -15 Pa, the pressure distribution that occurs in the room is more uniform and approaches the pressure value at the outlet, namely 95% of -15 Pa. The average pressure along the bed is still more positive than the pulmonary pressure, which is -133 Pa, so the patient is still comfortable.

5. Conclusion

A numerical study of three-dimensional flow characteristics in isolation rooms with negative pressure differences resulted in the following conclusions:

1. In the comparison charts of velocity and temperature to variations in pressure values, it is shown that there is a similar trend. The variation of -15 Pa shows almost uniform pressure distribution with outlet pressure, so the variation of -15 Pa is the best pressure difference.
2. In the comparison charts of velocity and temperature to variations in the patient's bed position, different values are shown at specific points, and there is a distinct trend so that the configuration of the patient's bed position affects the airflow characteristics in the isolation room.
3. In an isolation room with one bed, the velocity above the bed is an average of 0.087 m/s which is still below the comfortable airspeed limit of 0.2 m/s. The average temperature above the bed is 297.48 K, which is still within the comfortable temperature limits of 297.5 K and 300.5 K. The average pressure above the bed is still within the safe limits of the patient's breathing, which is - 1mmHg or -133 Pa.
4. In an isolation room with two beds, the velocity is above the bed with an average of 0.055 m/s at the bed near the inlet and 0.04 m/s at the bed near the outlet, which is still below the comfortable air velocity limit. The average temperature above the bed is 297.65 K at the bed near the inlet and 297.97 K at the bed near the outlet, which is still within the comfortable temperature limits of 297.5 K and 300.5 K. The average pressure on the bed is still within the safe limits of the patient's breathing, which is -1mmHg or -133 Pa.
5. The configuration of a two-bed isolation room is not recommended because there is a vortex flow right above one of the beds, which can endanger the patient.

Acknowledgments

The authors have stated that there is no conflict of interest.

References

[1] VACIC, "Guidelines for the classification and design of isolation rooms in health care facilities," *Victorian Advisory Commitee. Infection Control*, 2007.

[2] A. S. Comitee, "Ventilation of healthcare facilities," *ANSI/ASHRAE/ASHE Standard 170-2008*, no. 2, p. 6, 2008.

[3] D. W. Bearg, *Indoor air quality and HVAC systems*. Routledge, 2019.

[4] 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. 75–92, Springer, 2019.

[5] N. J. Adams, D. L. Johnson, and R. A. Lynch, "The effect of pressure differential and care provider movement on airborne infectious isolation room containment effectiveness," *American Journal of Infection Control*, vol. 39, no. 2, pp. 91–97, 2011.

[6] A. H. . A. M. Putra, "Fisiologi ventilasi dan pertukaran gas," *Respiratory*, p. 30, 2016.