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Computational Study for Allocation of Supply Vent in HVAC for Negative Pressure Isolation Room

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Abstract

Air as a high speed transportation agent, made airborne infectious diseases like COVID-19 fast-spreading and dangerous.The COVID-19 outbreak turned into a worldwide health emergency. For those who had been infected, the primary concern following infection was taking the utmost preventative measures. Although negative pressure room were generated to gets rid of these problems. Negative pressure rooms control the spread of infectious diseases, as these rooms had lower pressure than the atmospheric pressure. Appropriately designed HVAC systems provided satisfactory indoor air quality and lessened the conditions that boost health-care-associated pathogens. Correctly placed component affect the ventilation system. This present study has been focused on the allocation of supply vent to optimize the ventilation system of the negative pressure room. Effect of the different position of supply vent was also performed. For this CFD, simulation was done in the SIMSCALE software; negative pressure, temperature and velocity all over the room were observed. This study, based on comprehensive numerical simulations, consistently demonstrated results in accordance with established standards. In terms of velocity, the system consistently maintained safe airflow levels. Temperature profiles affirmed the system's capability to sustain extended stability before gradual temperature changes, ensuring occupant thermal comfort. Pressure differentials consistently adhered to acceptable limits, contributing to a controlled environment and effective prevention of air contamination. These numerical findings underscored the system's efficiency in creating a secure and comfortable environment for occupants.

Keywords

ACH, Negative Pressure, SIMSCALE, Supply vent

1. Introduction

A negative pressure room comprises a ventilation system designed so that air flows from the corridor to the room, ensuring that adulterated air doesn't escape from the room to other regions of the hospital area. Naturally, the flow of air is from higher pressure to lower pressure. Uninterrupted air flows into the room beneath the door when negative pressure exits, preventing airborne particles from escaping into the corridor. Usually, such rooms are found in the hospital wards, particularly during the quarantine period. HVAC system is used to create a negative pressure space. HVAC systems ensure air is drawn into the room and contaminated particles, such as those patients in isolation, are not able to escape.

HVAC is a highly specialized sector, and critical care facilities like isolation rooms and operating rooms require special consideration since infected patients must be segregated from the outside environment to stop the spread of the infection and preserve their lives. An efficient negative pressure room is a crucial part of every healthcare facility. These rooms control the spread of infectious diseases. In hospital settings, these rooms prevent the spaces and are also referred to as airborne infection isolation rooms or negative pressure rooms. Also termed isolation rooms or negative pressure rooms, they keep patients with contagious diseases or those prone to infections. These rooms are generally used for infection control for diseases like COVID-19, measles, tuberculosis, etc.

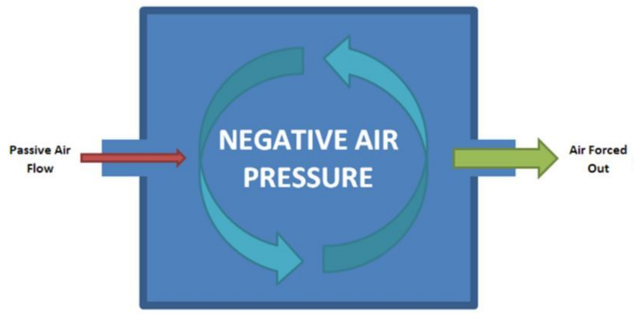

Figure 1: Schematic Diagram of isolation room

2. Literature Review

[1] Several layout configurations for exhaust air were suggested to improve ventilation effectiveness for infection control. In the simulation model, an air-jet curtain was introduced to provide added protection for medical personnel. Two simulation strategies were put forward: optimizing the arrangement of exhaust air grilles to enhance the ventilation system's performance and providing an additional air jet curtain positioned between the patient's bed and the medical staff. The findings indicated that positioning the exhaust air near the patient's head resulted in improved ventilation performance, and this effect could be further optimized by employing an air jet curtain. To create negative pressure or positive pressure room,[2] present a standard guideline which should follow while designing the operating rooms.

In order to examine the diffusion of airborne viruses inside the NP room with a mixed-mode ventilation system, CFD simulations were performed. The simulations presented indicate that the pressure distribution shows an elevated pressure near circular vents. The negative pressure room is competent at controlling the diffusion and spreading rate of virus objects.[3].

Operating rooms often have door opening. Contaminated air may flow inside the room when the door is opened. This study numerically investigated the transient airflow caused by opening the sliding door. The airflow driving mechanism through an open door is a combination of several factors, including temperature differences, pressure differentials, ventilation air flow, human passage, and the motion of the door itself. The door was considered an internal wall with negligible thickness. When the door was opened, airflow extracted from the OR was reduced while attempting to exhaust airflow. Both the OR exhausts flow and pressure dropped during the door's opening phase..[4]

(Zhonglin Xu, 2016)A supply vent should be positioned in the ceiling for supply in sensitive areas, ultra-clean regions, and seriously polluted regions. Simultaneously, the surrounding exhaust air openings should be set near the floor. In this way, clean air could be supplied to the breathing zone and the working area, then sent downward to the polluted floor area to be exhausted. Research, including insights from scholar Chan Fan following the SARS epidemic, has highlighted that an up-supply and down-return system effectively dilutes and removes pollutants. CFD simulations demonstrated that this kind of design could reduce the cross-flow of polluted air in the SARS ward. Also, it was known that 1.5 m above the floor in the breathing area of the medical personnel, contamination was greatly reduced.

3. Methodology

Input design parameters were collected from primary source as well as from secondary source. For computational domains, a simplified model of room was prepared geometry of room is given below.

Table 1: Geometry of Room

Name	X-direction	Y-direction	Z-direction
Isolation room	3.6	3.65	2.6
Anteroom	3.6	0.9	2.6
Bed	1.95	0.93	0.59
Air supply	0.6	0.6	-
Air outlet	0.6	0.6	-
door	0.88	-	1.9
window	1.16	-	1.62

Geometry of the models was produced by using CATIA V-5. To build a model, several geometric components were put together: a well-insulated, airtight space that limits the filtration of ambient air. CATIA V5 was used to generate a geometric model of the whole isolation ward. Any standard hospital room that has room for patients, caretakers, and other medical equipment qualifies as a negative pressure room. Since the default physical setup has not yet been established, the model was built using both primary and secondary data.

Standard rules and regulations were derived from the ASHRAE handbook. Handbooks from various authors and writers about the HVAC and negative pressure room were also looked upon. Various articles and research paper were also taken in consideration relevant to the topic. Some of the important considerations for the project are mentioned below:

1. The isolation room and corridor's pressure difference should be greater than 2.5 Pa[5].
2. Thermal comfort: temperature = 22°C to 27°C .
3. Air Change Per Hour should be greater than 12[6].
   If the air change value is below 12, there is high probability of occurrence of cross contamination and ventilation of room will be weak[7] .
4. Re-circulation of air in isolation room should not be done.
5. Velocity near patient should be less than 0.25 m/s.

The term "air change per hour" refers to how frequently air may be drawn into a space in a given hour. Higher ACH values help speed up the removal of contaminants from the space, but they also entail more refrigeration system tonnage and energy consumption; therefore, the ideal ACH values must be chosen.

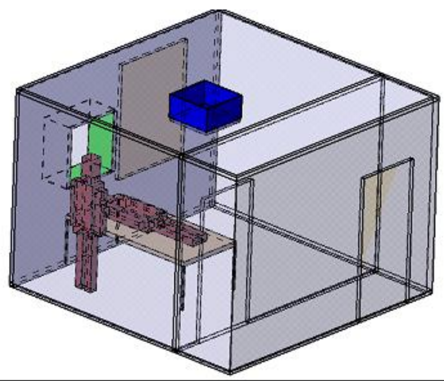

Figure 2: Solid Model of Isolation Room

Three model of isolation room was made by changing the position of the supply vent. Different locations of supply vent are shown in given table. In all three cases, position of exhaust vent is placed at 1000 mm above the floor at the head side of the patient as [4]concluded.

Table 2: Geometry Of Room

Cases	X-Axis L(m)	Y-Axis L(m)	Z-Axis L(m)
Case-1	0.75	1.2	2.6
Case-2	1.65	1.2	2.6
Case-3	2.55	1.2	2.6

Case '1' : - Supply vent located at bottom left side of the room ceiling in first case, the inlet is kept at bottom left of the isolation room. It is 750 mm from left wall.

Case ‘2’ : - Supply vent located at bottom mid side of the room ceiling The inlet is kept at bottom mid side of the isolation room.

Case ‘3’ : - Supply vent located at bottom right side of the room ceiling (750 mm from left wall) The inlet is kept at bottom right side of the isolation room. It is 750 mm from right wall.

Occupant’s head size was taken as (0.16*0.311*0.16)m and body’s size was taken as (0.3*0.692*0.2)m [8] .

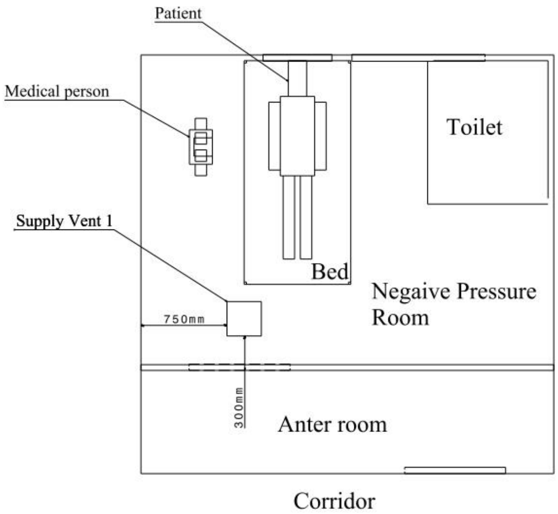

Figure 3: Top View of Supply vent 1

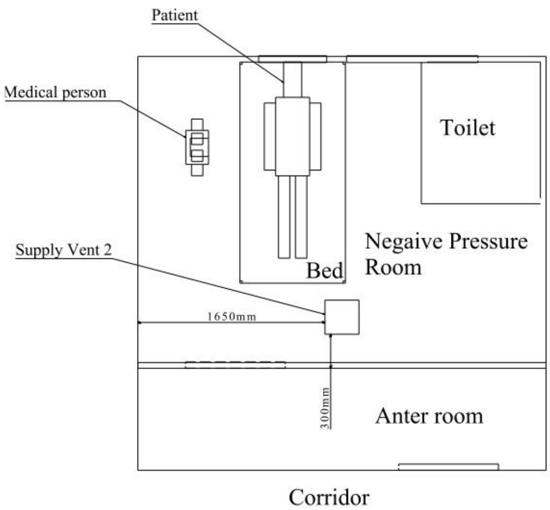

Figure 4: Top View of Supply vent 2

4. Numerical Methods

CFD has been crucial to many domains, especially for the inflow and outflow. The Reynolds Averaged Navier Stokes equation is used in all CFD simulation and is primarily employed for the point correlation of the changing velocities. The air enters into the room through inlet. As they adhere the law of conservation, momentum and continuity equations are used as the governing equation in this analysis.Turbulence models commonly used in CFD application are RANS-based models, especially two equation models. K- Omega turbulence models capture the effect of turbulent conditions.

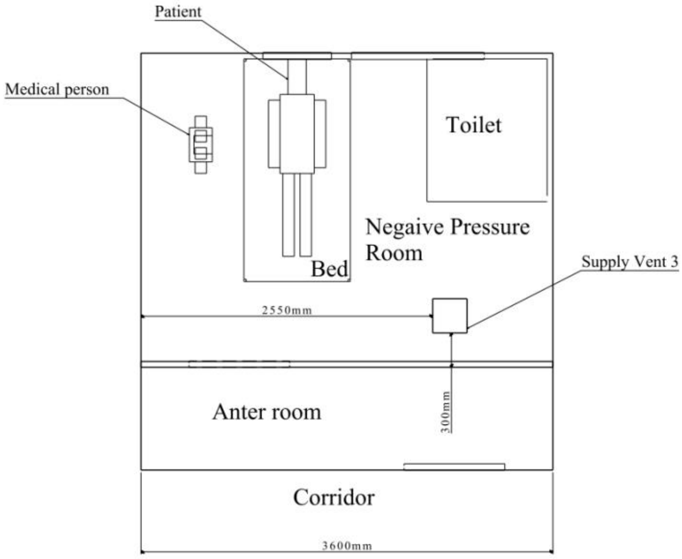

Figure 5: Top View of Supply vent 3

It belongs to the family of Reynolds-averaged Navier-Stokes turbulence models (RANS) in which all effects of the turbulence are modeled. Two transport equations are solved that take into account historical effects such as convection and diffusion of turbulent energy.

Reynolds Naiver-Stokes conservation equation were applied to solve momentum, mass and energy.

Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho v = S_{source} \qquad (1)$$

Momentum conservation equation

$$\rho \cdot \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} \right) = \rho \vec{g} - \nabla p + \mu \cdot \nabla^2 \vec{v} \qquad (2)$$

Where, The variables ρ, v, p, and g represent the air density, velocity, pressure, and gravitational acceleration, respectively.

Energy conservation equation

Often the energy of a fluid is defined as the sum of internal (thermal) energy I, kinetic energy 1/2 (u2 + v2 + w2) and gravitational potential energy.

The CFD (Computational Fluid Dynamics) software SIMSCALE was applied for the analysis. Air was taken in consideration.

5. System Description

A square air inlet mounted on the ceiling with dimensions of 600*600 mm was used to deliver supply air to the room. An exhaust fan positioned on the wall next to the patient’s bed was used to remove exhaust air. Two occupants had been considered in the study. One is patient; lying on the bed and other is care giver standing right next to patient. Anteroom acts as a barrier to prevent pressurization loss and escape of contaminated air from the isolation room.[9]. Chance of contaminating the corridor is higher than the anteroom. Anteroom keeps corridor away from the negative pressure room, which minimizes the possibility of direct contamination to the corridor. Door of anteroom is kept at right side for analysis.

5.1 Boundary Condition

During a 1000-second duration, numerical simulations were conducted and documented. Below are the numerical simulation's boundary conditions. Radiation coming from the window affect the ventilation of room. Radiative source was taken as 800 w/m2 [10]. As there are two occupants inside the room, they emit heat fluxes 42 w/m2[11].

Table 3: Boundary Condition for numerical simulation

Parameter	Supply air	Exhaust air
Flow rate (m3/s)	0.1138	-
Pressure (Pa)	0	-3

6. Case Study

The room was able to receive airflow with a total air exchange rate of 12 ACH and a volumetric flow of 0.1138 m3/s through the use of a supply vent. Geometric model with supply vent location at three different locations had been studied. In each of these cases, the door's placement was consistently positioned on both the left and right sides of the room. Given the frequent usage of this door, a notable aspect of this study was the deliberate choice to maintain the door in an open configuration. Consequently, this leads to a total of six distinct scenarios, all within a room inlet of 600x600 dimensions, featuring an 800-sized outlet. These six scenarios follow by a series of terms.

Table 4: Six scenarios

Case	Door Location
Case 1-a	Vent at left side of the ceiling with left door
Case 1-b	Vent at left side of the ceiling with Right door
Case 2-a	Vent at mid side of the ceiling with left door
Case 2-b	Vent at mid side of the ceiling with Right door
Case 3-a	Vent at Right side of the ceiling with left door
Case 3-b	Vent at Right side of the ceiling with Right door

6.1 Mesh Generation

For meshing the room SIMSCALE was used. An automatic generation of many levels of refinement was offered by simscale, according to the dimensions of the modeled room. Using a parametric hex dominating mesh builder, the 3D model was discretized. More than four million 3D elements were present in the mesh. Additionally, the boundary condition local refinement was included.

Pressure, velocity, temperature, and concentration levels were assessed using numerical simulations. Data was collected over duration of 1000 seconds.

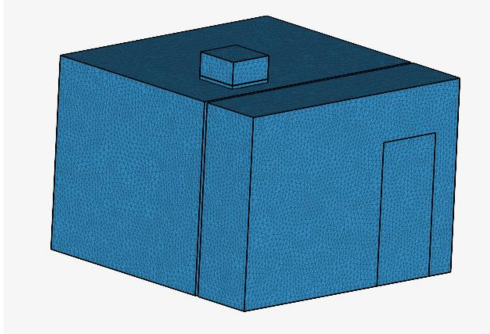

Figure 6: Mesh Generation

6.2 Sample Point

To maintain certain characteristics in the room, such as velocity, CO2 levels, and negative pressure, in order to achieve our ideal conditions. We have purposefully positioned sample points for measurement across the space. P1, P2, P3, and P4 are among these sample points; they were chosen with care to guarantee a comfort zone for patients and medical staff. We have also taken into account the flow pattern near around the patient

7. Result

The supply vent operates at a flow rate of 0.1138 m³/s, as indicated in the figure. It passes through the air system while preserving a static pressure of -3 Pa at the outlet. The flow vector diagram shows that air is drawn in through the inlet and exits through the outlet without mingling with the patient's exhaled air. This design effectively expels contaminated air from the room without diffusion.

7.1 Pressure Profile

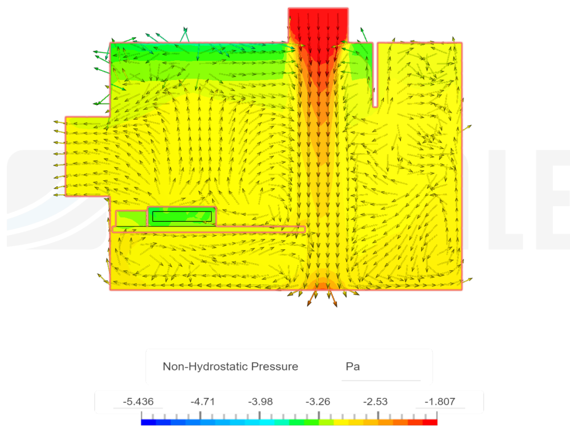

Figure 7: Pressure contour-case 1

As per ASHRAE standards, maintaining a pressure difference of more than -2.5 Pa between the interior and exterior of a room is necessary. The provided figure demonstrates the successful achievement of this requirement in Case 1, Case 2 and Case 3. This pressure difference has been consistently sustained throughout the entire room, including areas adjacent to both the patient and medical personnel.

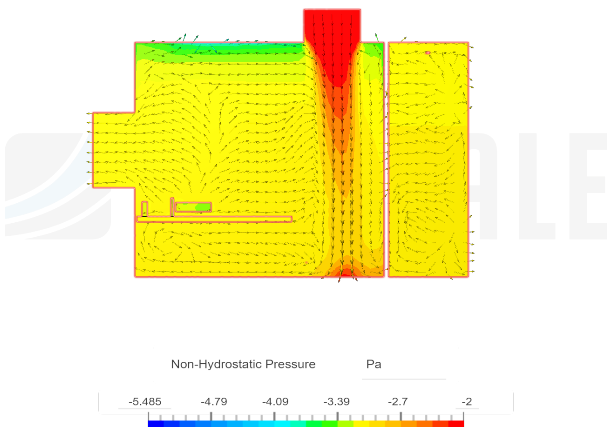

Figure 8: Pressure contour-case 2

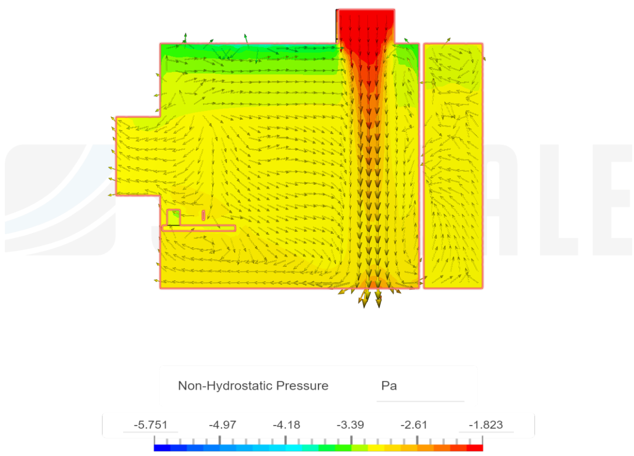

Figure 9: Pressure contour-case 3

Numerical simulation from 0 to 1000 seconds has been done continuously. The data has been collected with the time difference of 1 second.

Table 5: Pressure for different cases

Case	Pressure (Pa)	ASHRAE Range
Case 1-a	-2.8 to -3.2	-2.5 Pa
Case 1-b	-2.5 to -4	-2.5 Pa
Case 2-a	-2.9 to -3.2	-2.5 Pa
Case 2-b	-2.9 to - 15	-2.5 Pa
Case 3-a	-1 to -5	-2.5 Pa
Case 3-b	-2.9 to -3.2	-2.5 Pa

7.2 Pressure Difference at external door

The door acts as a gateway for air to pass in between the corridor and the room. Thus, pressure at the door has to be checked. If the pressure at the door is negative, then air won't pass into the corridor from the room.

Table 6: Pressure Difference at external door

Case	Pressure (Pa)	ASHRAE Range
Case 1-a	-2.9 to -3	-2.5 Pa
Case 1-b	-0.5 to -3.5	-2.5 Pa
Case 2-a	-2.9 to -3	-2.5 Pa
Case 3-a	-1.5 to -4	-2.5 Pa
Case 3-b	-2.9 to -3.4	-2.5 Pa

7.3 Temperature Profile

In the temperature vs. time graph, we initially maintained 300 K for the first 100 seconds. Subsequently, during the simulation, the temperature gradually increased to 302 K in Case 1, 302 K in Case 2, and 304 K in Case 3.

The capability to control and maintain temperature increases is crucial for occupant thermal comfort and can be effectively managed through an Air Handling Unit (AHU) in accordance with their requirements.

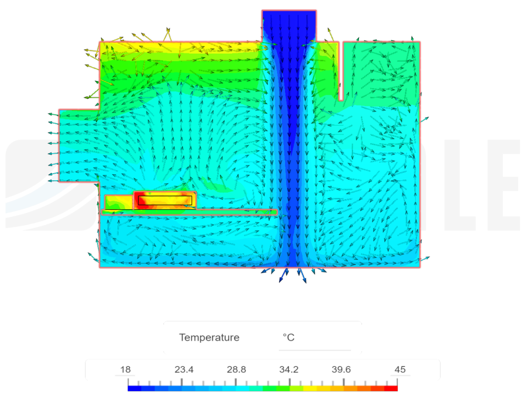

Figure 10: Temperature contour-case 1

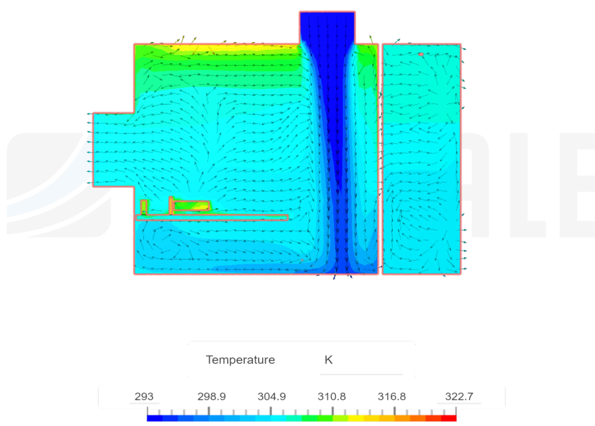

Figure 11: Temperature contour-case 2

Table 7: Temperature for different cases

Case	Temperature (K)	ASHRAE Range (K)
Case 1-a	293-302	295 - 300
Case 2-a	293-302	295 - 300
Case 3-b	293-304	295 - 300

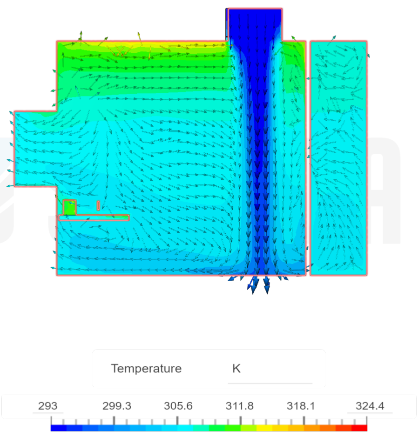

Figure 12: Temperature contour-case 3

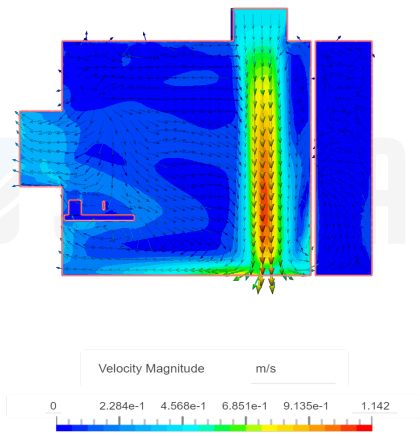

Figure 15: Velocity contour-case 3

7.4 Velocity Profile

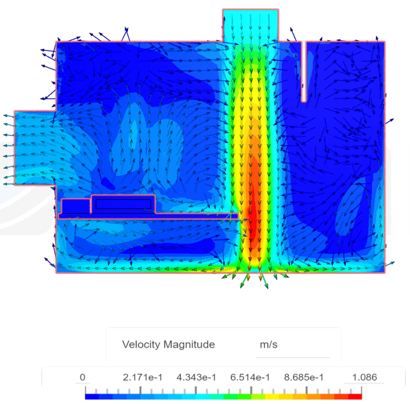

Figure 13: Velocity contour-case 1

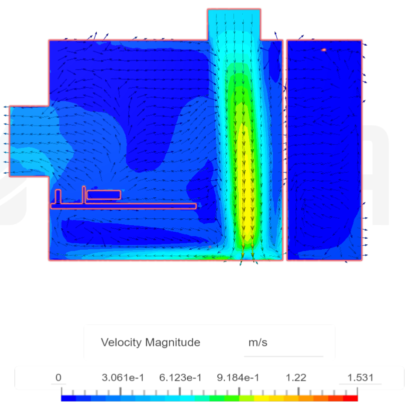

Figure 14: Velocity contour-case 2

In the analysis of velocity vs. time, it was consistently observed that the velocity remained below 0.25 m/s, which aligns with the specified standard. Air velocity inside the room was found less than 0.25 m/s and the velocity vector plot shows the flow of air from supply zone to exhaust zone.

In Case 1, the maximum velocity recorded was 0.033 m/s, significantly below the 0.25 m/s standard.

In Case 2, the maximum velocity recorded was 0.044 m/s, which fall below the standard.

In Case 3, the velocity remained at 0.062 m/s during various time intervals, also meeting the standard consistently.

Table 8: Velocity for different cases

Case	Velocity (m/s)	ASHRAE Range
Case 1-a	0.013 - 0.033	0.25(m/s)
Case 2-a	0.008 - 0.044	0.25(m/s)
Case 3-b	0.005 - 0.062	0.25(m/s)

7.5 CO2 Concentration

To assess the CO2 concentration within the isolation room, data from two distinct sources is considered: the patient and the medical personnel. The concentration of CO2 in an individual's exhalation is measured at 38000 PPM. The cumulative CO2 concentration is calculated for this simulation by combining the contributions from both sources. Given that the two sources create a total concentration of 76000 PPM, the simulation is run on that premise.

Given table difference is the outcome of the simulation of the model. The maximum CO2 concentration values at all four data points in Model 1 a continuously exceeded 1000 PPM throughout the simulation. Similarly, during the simulation period, the maximum CO2 levels in Model 2 a increased by 219 in Pt. 1, 229 in Pt. 2, 213 in Pt. 3, and 240 in Pt. 4. In Model 3 b, it is notable that throughout the simulation period, the concentration gains were observed to be 291 in Pt. 1, 90 in Pt. 2, 65 in Pt. 3, and 104 in Pt. 4. Importantly, these values remained below the threshold of 1000 PPM.

Table 9: CO2 Concentration

Case	CO2 Concentration (PPM)	ASHRAE Range
Case 1-a	1610 - 3560	1000 PPM
Case 2-a	219 - 240	1000 PPM
Case 3-b	90 - 291	1000 PPM

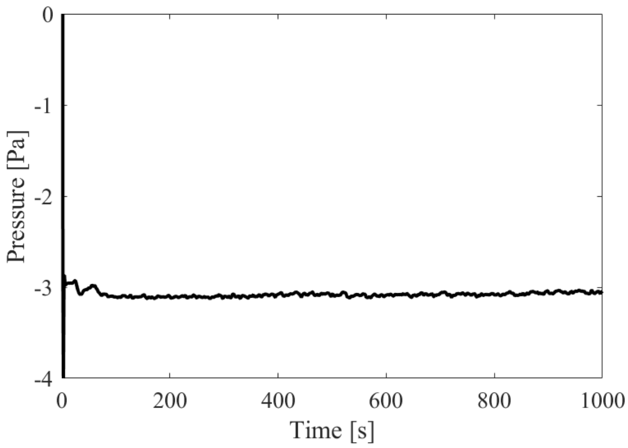

Figure 16: Pressure v/s time -case 1

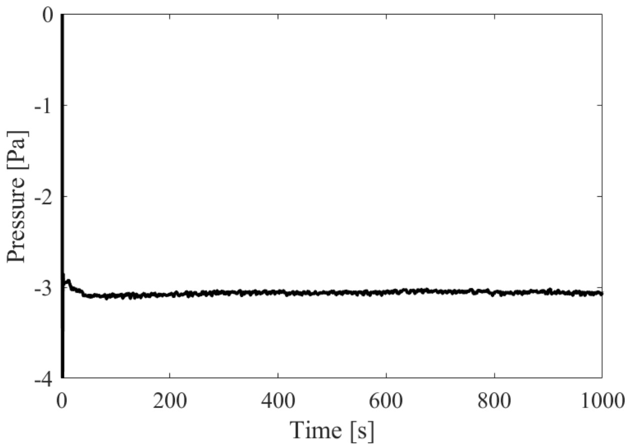

Figure 17: Pressure v/s time -case 2

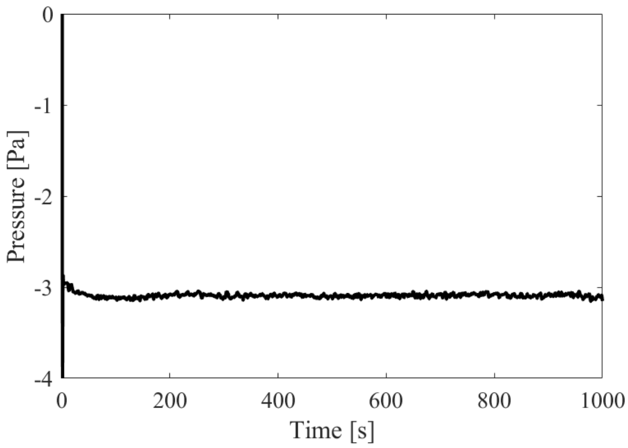

Figure 18: Pressure v/s time -case 3

7.6 Air Change Per Hour

Air change rates quantify the amount of air passing through a specific region relative to its volume. They are expressed as ventilation units. These rates are calculated to assess how well a place is ventilated relative to accepted norms, regulations, or guidelines. Although a high ACH value enhances the rate of contaminant removal, it also leads to increased energy consumption. Hence, optimal ACH should be selected, so we have computed the values of the selected models. The table shown provides the calculated ACH of all three models: model 1-a, model 2-a, and model 3-b.

[9]Air quantity (CFM) = (Vol. of room*ACH) / 60

Table 10: Calculation of ACH

Case	Obtained CFM	Calculated ACH
Case 1-a	254.47	12.655
Case 2-a	283.29	14.08
Case 3-b	268.05	13.33

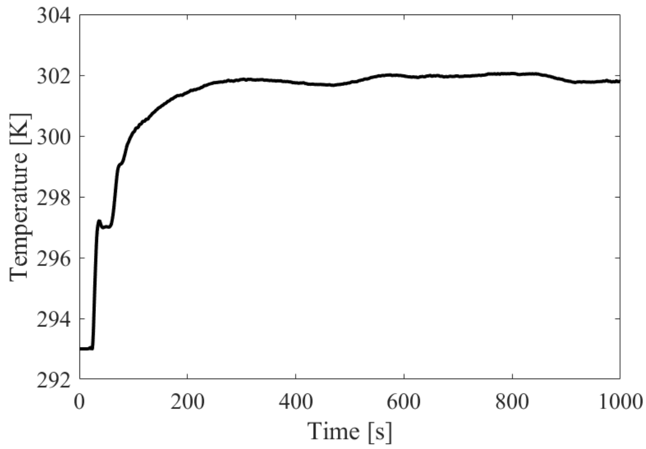

Figure 19: Temperature v/s time -case 1

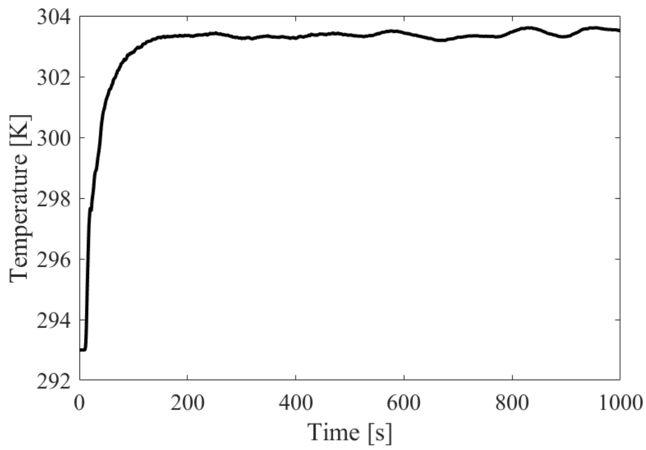

Figure 20: Temperature v/s time -case 2

8. Validation

In order to validate our findings, we performed adjustments to the mesh elements within the model optimized for pressure difference analysis. These modifications yielded values that exceeded -2.5 Pascal (Pa). After a thorough study of the simulation, for result confirmation, the satisfying cases of pressure difference models were checked for two mesh qualities: moderate and fine. Red indicates fine mesh quality in the simulation result, whereas blue indicates moderate mesh quality in the graph plot. One of the models is shown below.

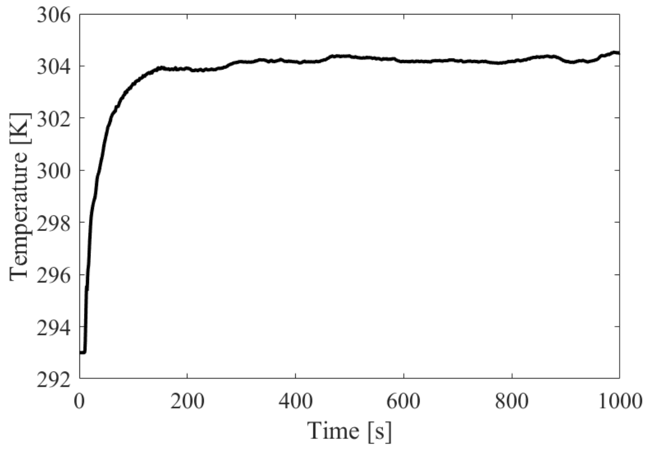

Figure 21: Temperature v/s time -case 3

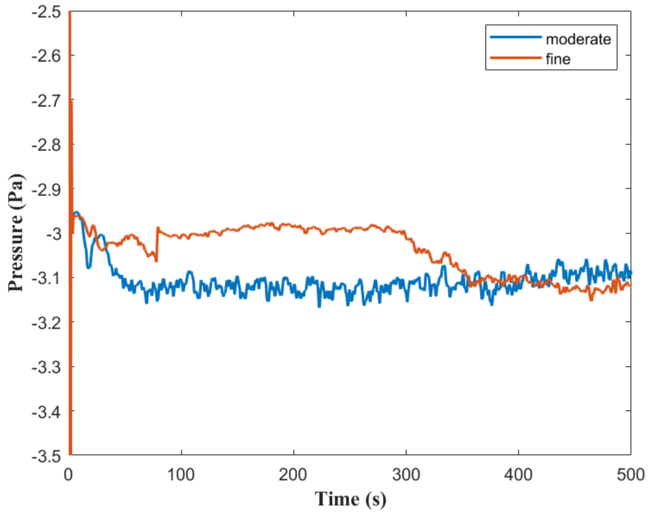

Figure 22: Pressure of Model 1-a in different mesh quality

9. Conlusion

The thorough analysis of Cases 1, 2, and 3 in relation to pressure, temperature, velocity, and ACH compliance with ASHRAE standards, in addition, yields insightful results. In models 1, 2, and 3, the most suitable door placement was determined. Models 1 and 2 indicated a preference for having the door on the left side to maintain the desired pressure difference, whereas model 3 achieved the required pressure difference with the door positioned on the right side of the room. During the assessment of pressure differences at the door in all simulated models, it was found that these three models, Model 1-a, Model 2-a, and Model 3-b, were well-suited and performed in accordance with the desired criteria for pressure maintenance at the door.

In regard to temperature control, when the maximum temperature was established as a boundary condition, it was slightly above the specified range. Conversely, when the minimum temperature was set as the boundary condition, it was slightly below the desired range. In each case, minor temperature discrepancies are seen, though they are all within manageable ranges. However, it is worth noting that these temperature variations can be effectively managed through the operation of the Air Handling Unit (AHU). AHU integration can be used to effectively correct deviations and ensure alignment with the required standard.

Furthermore, the velocity in all the models remained within the desired standards.The velocity profiles in each case comfortably meet ASHRAE requirements by maintaining speeds below the 0 point 0.25 m/s threshold, ensuring that the airflow is safe and under control

In Model 1-a, the concentration of CO2 was effectively maintained within the desired range. The ACH values also consistently exceed the 12 ACH ASHRAE criterion, indicating effective ventilation and strict adherence to the established standards. The calculated Air Changes per Hour (ACH) values met the specified standard in all of the models, indicating that the ventilation and air exchange rates were in compliance with the desired criteria.

In conclusion, these results demonstrate that the system can consistently maintain a safe and comfortable environment, with any minor deviations clearly correctable by wise interventions. Temperature is slightly unmatched with standards, Can be maintain with help of AHU.

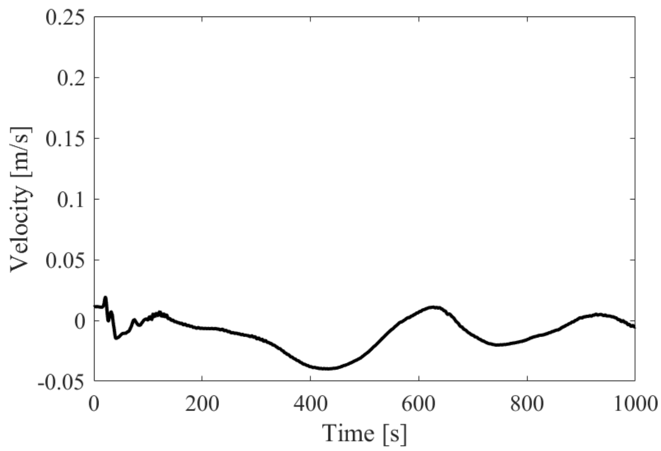

Figure 23: Veocity v/s time -case 1

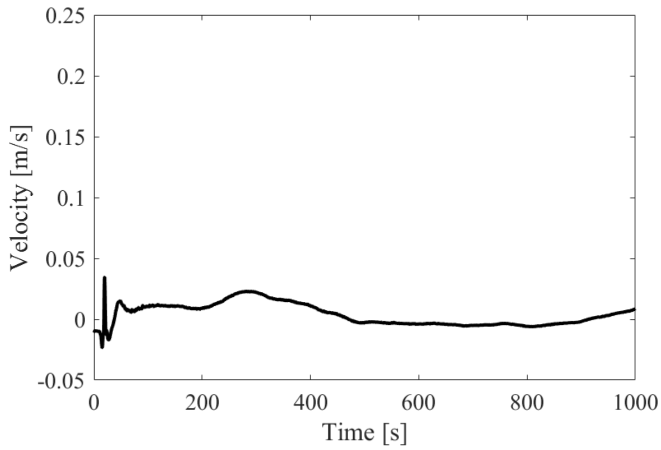

Figure 24: Veocity v/s time -case 2

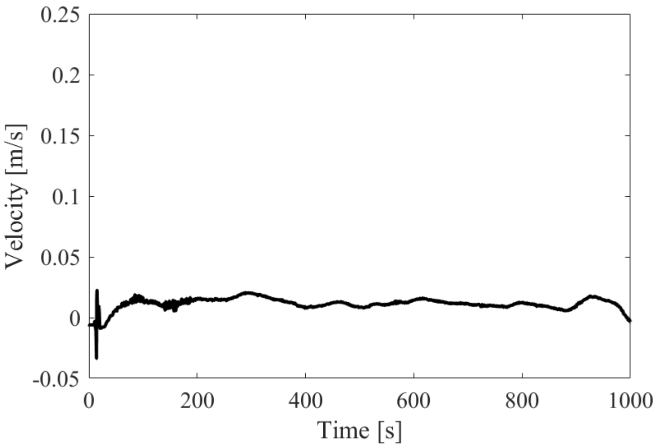

Figure 25: Veocity v/s time -case 3

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