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Impact of human–human virus transmission in an air-conditioned room with proper ventilation system

Chalumuru Manas, Pusapati Laxmi Narasimha Raju, Kethavarapu Naga Bharat Kumar, and Harish Rajan*

School of Mechanical Engineering, Vellore Institute of Technology, Chennai 600127, Tamil Nadu, India

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Abstract. As we are probably aware of certain infectious diseases that transmit from body to body because of perspiration or respiration of air from a human being containing strains of the infection, the goal of this investigation is to see how the infection is getting spread from a human residing in a closed area provided with air conditioner and with an appropriate ventilation framework that need to be involved to diminish infection dissemination in this enclosed area. Considering the present COVID-19 situation, it is important to discover the effect of infection spread to an individual contagion source. An appropriate CFD-model giving analysis of infection transmission from individual to individual in an air-conditioned room would give results to understand such situations. Likewise, this examination would help in determining the velocity, temperature, and particle contours in a characterized walled area. Besides, we have displayed various nooks utilizing different ventilation frameworks to discover which framework would give better outcomes to decrease infection transmission. Our investigation would provide how varying flow rates in a room at an outlet could be effective in reducing virus dissemination, as this model could be applied to cafes, cinemas, inns, and above all emergency clinics where individuals remain in an enclosed air-conditioned room.

Keywords: COVID simulations / Ventilation system / Fluid dynamics / Isolated room / Particle contours

1 Introduction

Infectious disease such as, corona-virus disease also known as Covid-19 in 2020 is the most dangerous health disease which is best moderated by conscious arranging at the health system level. This outbreak has caused huge losses to global economies and the shattered lives of many people. It is imperative to control this infection spread to limit further damage. This implementation requires coordination between general health and medical care conveyance systems. Since the transmission of this virus, there have been various issues discussed related to the cause of the spread. Of these issues addressed by various health organizations, the virus is transmitted through droplet transmission, coming in contact with a source containing the pathogen. The WHO organization declared [1] this virus to be transmitted from person to person, droplets, contact, and various other modes. This pandemic has also occurred in 2003 and was called SARS-CoV which involved similar symptoms.

To limit the spread of these respiratory diseases (COVID-19) it is necessary to reduce the exposure. Especially in hospitals and other indoor environments where human exhalations of form sneezing and coughing produce particle droplets contaminating the room. Reference [2] has suggested ways to subsequently, these particles or droplets may encounter another person increases the probability of being infected. So, at most care should be taken in hospitals where there is a chance to protect doctors and other front-line workers dealing with infected patients. Reference [3] designed a ventilation ward using CFD for minimizing the spread of infections. Hospital pandemic readiness designs commonly incorporate conventions for taking care of a flood of Infectious patients. The other person inside the room just act as a bluff body like other bodies inside the room, we placed the body just to make the simulation more likely to the practical simulation Hospitals need to react quickly in the event of an emergency. Setting up a proper ventilation system and understanding the flow pattern of droplets in isolation wards could help prevent disease spread [4,5] has undertaken a CFD study to analyze the steady operation of the ventilation system inside an operation theater. There is certain uncertainty in various reviews on how many particles are released during sneezing and coughing. Reference [6] various experts have conducted wide research to find the size of droplets, understand particle flow. A maximum velocity range of 6–28 m/s has been detected, and the cough was found to expand linearly in the initial stage [7–11]. It was found that most droplets from coughing range from 0.3 micrometer to

* e-mail: harish.r@vit.ac.in

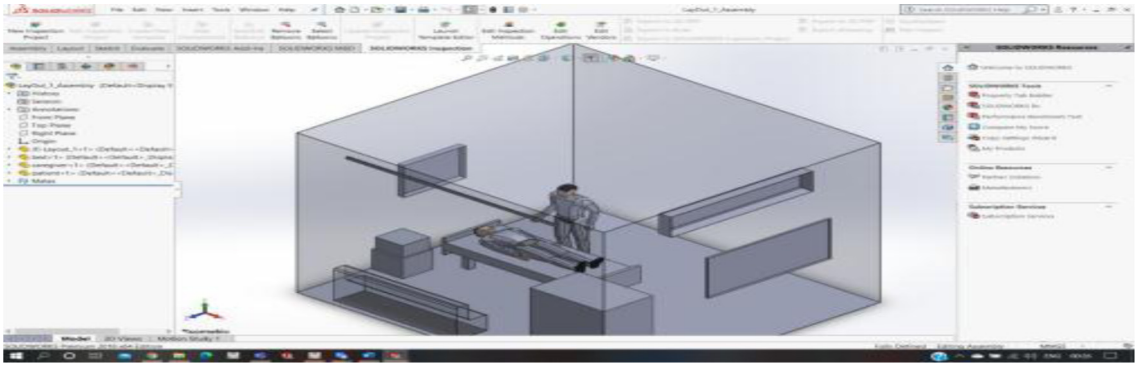

Fig. 1. Isolation room assembly.

10 micrometer. To provide protective measures various methods are being followed of these emergency clinics utilize negative-pressure airborne infection isolation rooms (AIIRs) to house patients with suspected or affirmed airborne contagious contamination. Many hospitals and other indoor places have reported using the HVAC system which can control the air quality and provide safe and reliable indoor conditions. Reference [12] has concluded that effective ventilation rates in indoor environments are an efficient way to prevent contamination. These HVAC systems should be designed in a manner suitable for negative pressure rooms and provide better air quality. Maintaining a negative pressure room would provide lesser droplets containing pathogens to spread outside the room minimizing the virus transmission. Reference [13] used the CFD model to understand the reliability and efficiency of the ventilation system in controlling air-quality. Reference [14] performed CFD simulation to study the airflow behavior of sneezing and coughing droplets in an aircraft-cabin and their results indicate the spread of particles to passengers in cabin at various flow rates.

In this paper, we have simulated a model considering an effective ventilation system to understand the flow of aerosol particles released through coughing and these simulations were conducted assuming no leakage losses from the room. The required calculations for an air conditioner to operate in indoor environments maintaining thermal comfort was performed. Reference [15] discrete phase modelling experiment involving flow of particles which illustrate an interaction between different particles. Reference [16] discusses about the movement of asphalt particle in a crude oil refinery, discrete phase modelling was used to simulate their behavior at various flow rates. Like [17–20] many authors have carried out CFD simulations to study ventilation patterns in isolation rooms using various approaches. To understand and reduce virus diffusion we have considered transient simulations over 60 seconds with the K-epsilon turbulence model to perform the simulation. Also, to track the coughed particles discrete phase modeling with required injection parameters was used in the simulation. With the help of academic software ANSYS FLUENT 2019 the simulations were solved providing us with the required results. The main objective of this analysis is to find the number of particles escaped at various outflow and coughing conditions and to understand the flow path of aerosols released from the patient mouth lying on a bed.

2 Methodology

The initial layout model used for simulation is designed in solid works, other room equipment's like air-condition, sofa, television and tube light were also designed to check their interaction with particles as some aerosol droplets containing pathogen might stick to these appliances and might be a significant source of virus transmission. A human manikin system for patient and caretaker was also designed in solid works with a mouth inlet for the patient through which particles come out. The AC-inlet vent was placed on top of the room wall and the outlet was placed over patient's head, considering this outlet position would provide optimal performance in removing virus-containing droplets. The study is basically to determine how the virus particles will behave inside a negative pressure room, and thermal study is done additionally to know the thermal comfort of the body. Furthermore, the outlet flow condition was designed to circulate air in the room at a flow rate greater than the inlet condition. As this condition would provide the necessary pressure to remove virus particles.

2.1 Design and simulation

2.1.1 Isolation room construction

The chamber designed with the help of solid works designing tool is assumed to have no anteroom and leakage of air to surroundings. The 3D layout is shown in Figure 1. The width, length and height of the isolation room are length = 3.36 m; width = 3.02 m; height = 2.68 m, respectively.

Figure 1 the isolation room is installed with all the necessary facilities like TV, Fridge, visiting chairs or sofa, patient bed, Heart Rate monitor with the following dimensions is designed.

An independent ventilation outlet and AC air inlet are established in the room. The total volume of the room is calculated to be $3.36\,\text{m} \times 3.02\,\text{m} \times 2.68\ \text{m} = 27.194\ \text{m}^3$.

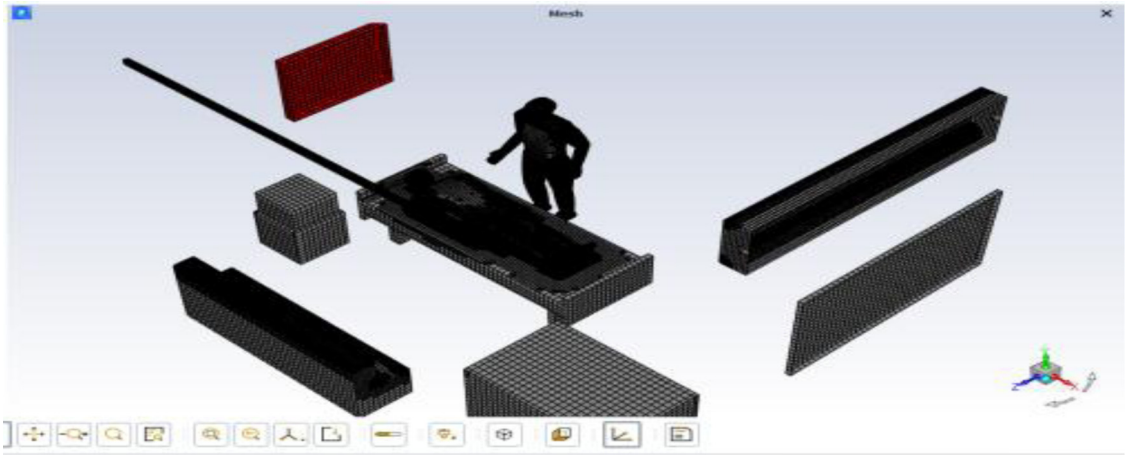

Fig. 2. Layout with air inlet and outlet.

Table 1. Mass flow rate at different velocities.

Velocity of cough (m/s)	Mass flow rate of cough
1	0.158
5	0.79
10	1.58
15	2.37
20	3.16
25	3.95
30	4.74

2.2 Independent air supply and exhaust system

The ventilation system in the isolation room consists of an air supply system and an air exhaust system. Figure 2 gives the layout with air inlet and air outlet along with the other objects inside the room.The Width and length of the outlet vent are designed to be 0.54 m and 0.67 m respectively. The outlet boundary conditions are adjusted at different mass flow rate condition's concerning the inlet mass flow rate to maintain negative pressure inside the room. The inlet mass flow rate is calculated and corresponds to 0.10909 kg/s to maintain 12 ACH inside the room concerning standards. According to various other rules listed a minimum of 12 ACH is required to maintain the proper air circulation in the isolated room. The Area of inlet and outlet designed were 32652.69 mm^2 and 0.36 m^2 respectively. Table 1 shows the cough velocity and the mass flow rate of the cough, that should be considered as one of the boundary condition while setting up the simulation To keep track on how changing outlet flow conditions will impact the behavior of virus particles, we have incremented the flow by 10% more than the inlet condition up to 6 intervals to the maximum condition of 70% mare than the inlet boundary condition.

2.3 Patient and caretaker

The simulation setup of a patient and a caretaker lying beside the bed in the isolation room. Of these patients, model is considered to be releasing microscopic virus particles, whereas the caretaker was placed right beside the patient bed to look over his probability of being infected. Besides, the patient and caretaker release certain heat and it is imperative to provide thermal comfort for the human body in an enclosed room. So, the required air inlet calculations were conducted to provide the optimum temperature required for a human. Simulations were conducted in ANSYS FLUENT to provide surface temperature results. Reference [13] has conducted experiments and numerical analysis related to thermal comfort and ventilation systems of patient and health worker in a room . Figure 3 is the caretaker model used for simulation.

3 Numerical calculation

3.1 Airinlet calculations

Air circulation per hour = 12 ACH
Volume of the room = 27.194 m^3 = 960 ft^3

$$\text{Air-flow} = \frac{\text{ACH} \times V}{60} = \frac{12 \times 960}{60} \quad (1)$$

V = volume of the room; air-flow = 192 CFM = 0.09061 m^3/h; area of inlet = 32652.69 mm^2 = 32652.69 × 10^{-6} m^2.

$$\text{Velocityofairatinlet} = \text{Airflow at inlet/Area of the inlet} = (0.09061\,m^3/s)/(32652.69 \times 10^{-6}) \quad (2)$$

Velocity of air at inlet = 2.774 m/s

$$\text{Mass flow rate of air at inlet} = \rho_1 \times a_1 \times u_0 = \rho_1 \times \text{air} - \text{flow rate}. = 1.204 \times 0.09061 \quad (3)$$

Mass flow rate of air at inlet = 0.10909 kg/s; ρ_1 = density of air; a_1 = area of inlet; u_0 = velocity of air at inlet.
Cough velocity at mouth:

$$\text{Area of mouth inlet} = 158.98 \times 10^{-6}\text{m}$$

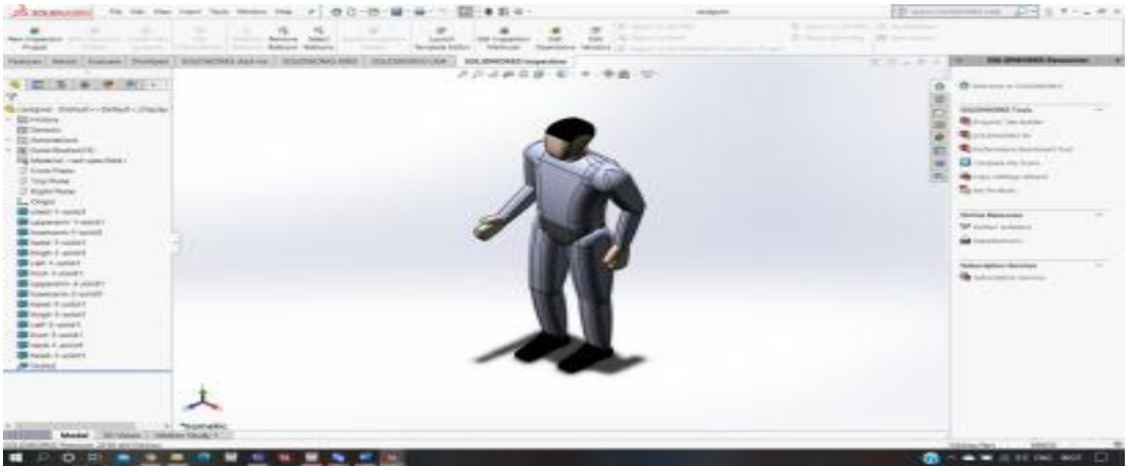

Fig. 3. 3D model of caretaker.

$$Q = A \times u \tag{4}$$

$$\text{Mass flow rate of each cough} = \rho^2 \times A \times u. \tag{5}$$

A = area of the mouth; u = velocity of the cough; ρ^2 = density; Q = discharge.

4 Simulations

Airborne infection isolation rooms (negative pressure rooms) prevent patient-released pathogens from escaping outside the room whereas, these infectious pathogens trapped inside the room need to be diluted which requires constant air circulation inside the room. In this study, negative pressure rooms are designed to study how an infectious particle behaves when the outlet mass flow rate increases. According to ANSI/ASHRAE/ASHE Standard recommends having at least 12-times air change per hour (ACH) for hospital applications, to facilitate effective ventilation. Where all the air inside the room is passed through a HEPA filter to remove 95% to 99% of the contaminants before they are released to the outside ambient air. A centrifugal blower with backward-facing blades is generally used downstream of this ventilation system to create the required negative/suction pressure.

4.1 Geometry clean up in design module

Using SolidWorks, Ansys 19, and Figure 4 we built a CAD model that includes a patient lying on a bed in a 960ft^3 room. Based on research and CFD-based-design optimization, the exhaust ventilation duct was placed on the wall right above the patient's head and the inlet vent was positioned in such a way that ventilation air directly sweeps the patient's head and trunk regions and moves to the ventilation outlet. This ventilation design minimizes re-circulation of the contaminants in the room and makes the room safer for the medical staff and other occupants. The minimum flow rate required for 12 ACH is approximately 192 CFM for a room volume of 960 cubic feet. To remove these particles as mentioned earlier outlet flow rate was designed to be greater than the inlet flow condition.

4.2 Meshing

Meshing is a crucial part while conducting simulation as a meshing determines the accuracy of results. Finer the mesh more accurate the results are, but to compute such large fine-mesh it requires large computational memory and consumes a lot of time to provide results. So, keeping in mind these aspects Figure 5 we had meshed the model in Ansys meshing tool using the cut cell method which maintains the optimum orthogonal quality of mesh recommended by ANSYS. Ansys have discretized a fine mesh with 1741387 elements and 1933770 nodes Later, named selections for the CFD model were defined for respective utilities as walls, fridge, TV, bed, Care-taker, Patient, Sofa Or chair, Air-inlet to the room, and the outlet boundary. Then the file was updated to Fluent, where The inlet boundary was defined as a Mass flow inlet open to the isolation room and the inlet direction was set by 90-degree or normal to the inlet duct and the outlet condition was considered to be mass flow outlet. The residual for mass, continuity and energy equations are set to a very small value of 10e^{-6}.

4.3 Pre-processing or setup

In the simulation, the RNG K-ε model was used taking into account the low-Reynolds number flow in the system. For the injection of particles from mouth, discrete particle-phase modeling was incorporated, this method requires us to enter the physical parameters of particles being injected in a period. We have used an inert particle model with a uniform diameter and coughing period of 1s. Furthermore to track the fluid particles in a turbulent flow random walk model (stochastic modeling) was incorporated. Microscopic particles with a diameter of 0.31e–6 were generated with a velocity ranging from 1 m/s to 30 m/s with a difference of 5 units to compute the flow of the expelled Particle from the patient's mouth. Discrete particle modeling would provide

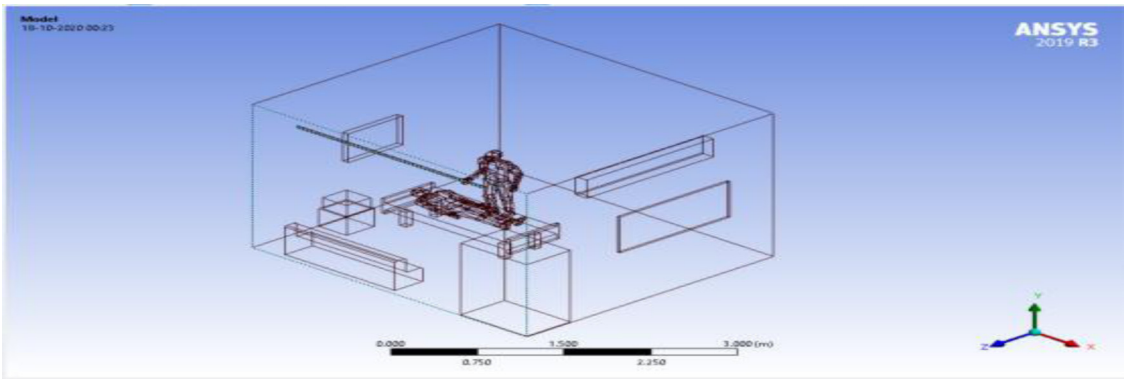

Fig. 4. 3D layout of room layout.

Fig. 5. Isolation room fine mesh.

a better understanding of the diffusion of particles containing a virus inside a room. Here nearly 3198 particles are said to be injected or expelled out of the patient mouth. The properties and the behaviour of these microscopic particles are studied at different velocities of cough and different outlet boundary condition.

4.4 Boundary conditions

Figure 6 the option should be trapped so that the microscopic particles that are coming out of the mouth will get trapped on these surfaces. The boundary conditions are a very crucial and important parameter that is given in Table 2 and Figure 7. The surfaces like sofa TV fridge monitor and Room walls are considered to be wall surfaces and in the DPM sections, the option should be trapped so that the microscopic particles that are coming out of the mouth will get trapped on these surfaces. Except the human body effected with virus, remaining all the objects inside the room act as a non thermal walls. This reduce the computational time and makes the simulation close to the expected results. The air coming from the inlet is considered to flow at the rate of 0.10909 kg/s and with a temperature of 293.15 K.

The air going out from the ventilator is considered to be a mass flow outlet with an initial mass flow rate 10% higher than the inlet mass flow rate that is 0.119999 kg/s and further, these values are increased by 10% with an interval of 6 units to study the behavior of the particles. The maximum outlet boundary condition in this paper is considered to be 70% more than the inlet boundary condition that is 0.185453 kg/s.

The particles coming out of the mouth is considered to be velocity inlet. the velocity of 1 m/s to 30 m/s with a difference of 5 m/s are considered to be the cough velocity to the particle velocity coming out of the mouth.

5 Results and discussions

These microscopic particle trajectories from the patient's mouth region were rendered using Ansys Animations tool. Based on the solution provided the microscopic virus particle trajectories are directly ventilated outside without any re-circulation in the room at 1 m/s in all the cases except at the condition of 0.11999 kg/s mass flow rate at the outlet boundary. It also shows that as the velocity of the virus particles from the mouth increases the number of particles tracked inside the room increases, this happens because Particles are moving with a higher velocity so the time or suction needed to ventilate the particle out from the outlet boundary is less and it also shows that as the outlet

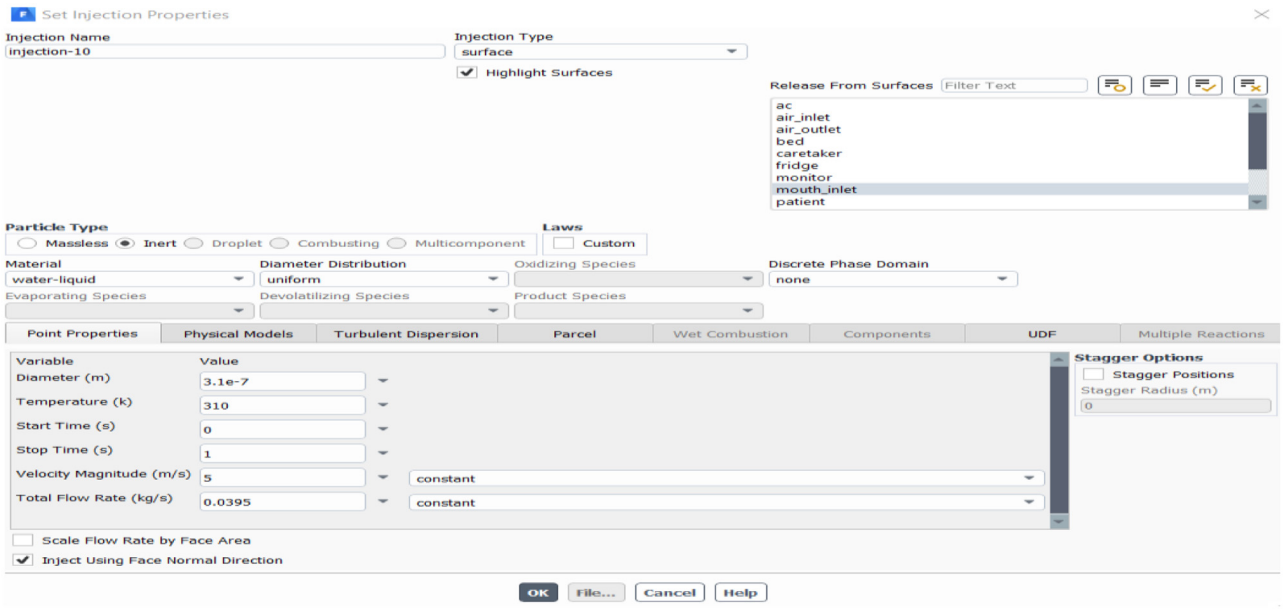

Fig. 6. Particle injection properties.

Table 2. Boundary conditions applied.

S. no	Boundary name	Boundary type	DPM
1	AC	Wall	Trap
2	Air_Inlet	Mass Flow Inlet	Escape
3	Air_Outlet	Mass Flow Outlet	Escape
4	Bed	Wall	Trap
5	Care_Taker	Wall	Trap
6	Fridge	Wall	Trap
7	Monitor	Wall	Trap
8	Mouth_Inlet	Velocity Inlet	Escape
9	Patient	Wall	Trap
10	Room Walls	Wall	Trap
11	Sofa	Wall	Trap
12	Tube Light	Wall	Trap
13	TV	Wall	Trap

mass-flow increases the number of particles tracked inside the room diminishes. These results indicate that increasing the outlet mass flow boundary condition will eventually ventilate a greater number of particles through the outlet duct. To maintain or provide a better and safe environment inside the room, increasing the mass flow rate at the outlet boundary is recommended.

As we can see from Figures 8 and 9 the inlet mass flow rate to the room recirculates to all the corners of the body at the minimum and maximum condition this tells us that the provided mass flow rate is sufficient to maintain a comfortable air circulation inside the room. Figure 10 describes the microscopic particles coming out from the patient mouth. Figure 11 From the graphs, as the magnitude of the mass flow rate increases at the outlet boundary condition, the time is taken to ventilate the virus particle from the room decrease.

5.1 Output parameters

To get the output parameter the dams report should be initialized to know the value of mass flow rate flowing out through the vent concerning time.

According to the results in Figures 12–18, fluctuations observed in patient temperature profile was due to the minuscule amount of air flow between patient and bed. whereas for care taker his body temperature was main-

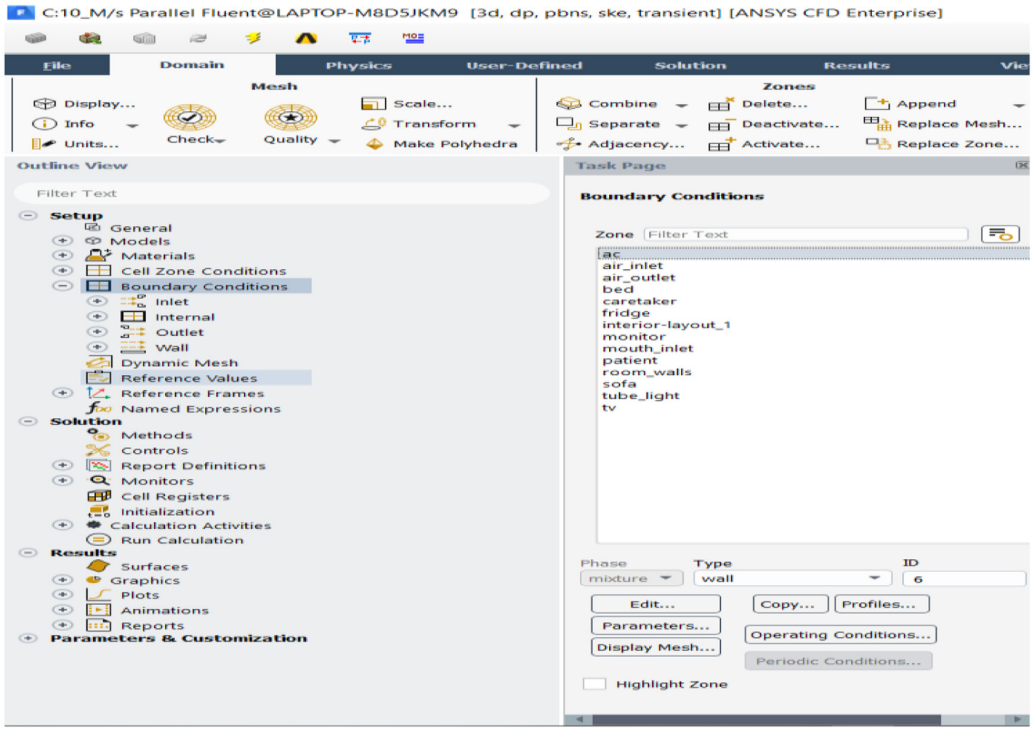

Fig. 7. Boundary condition of different surfaces.

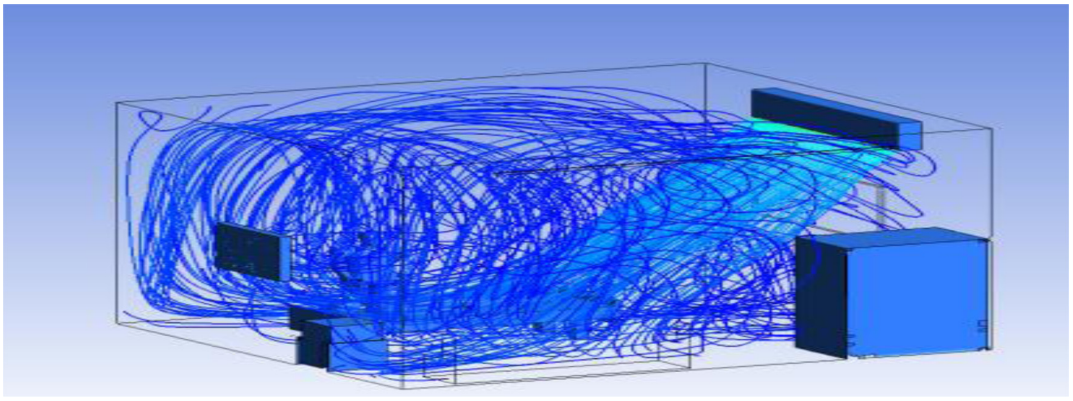

Fig. 8. Streamline flow from AC inlet.

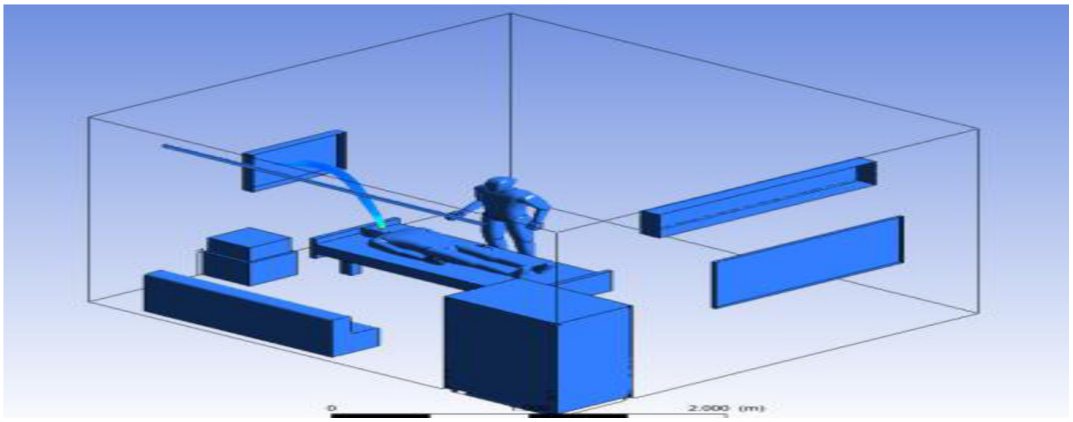

Fig. 9. Streamline flow from patient mouth.

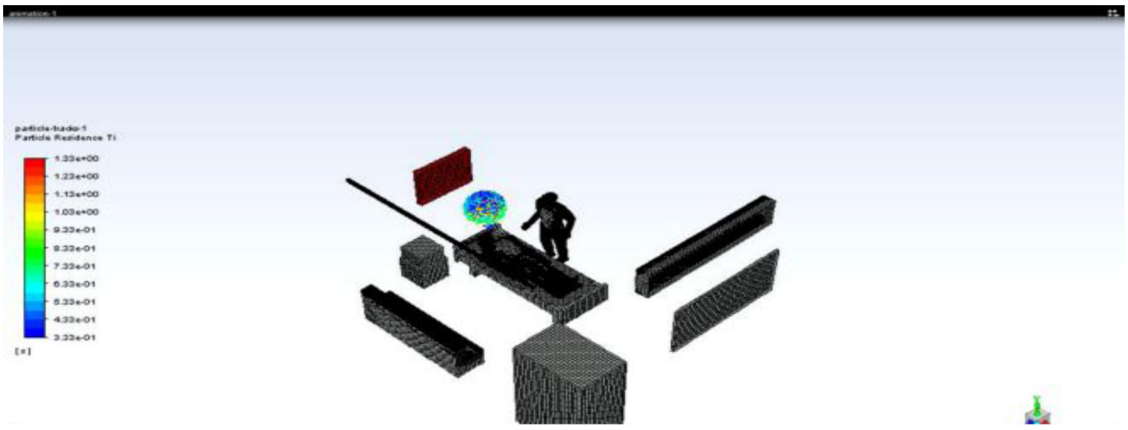

Fig. 10. Particle injections into the room.

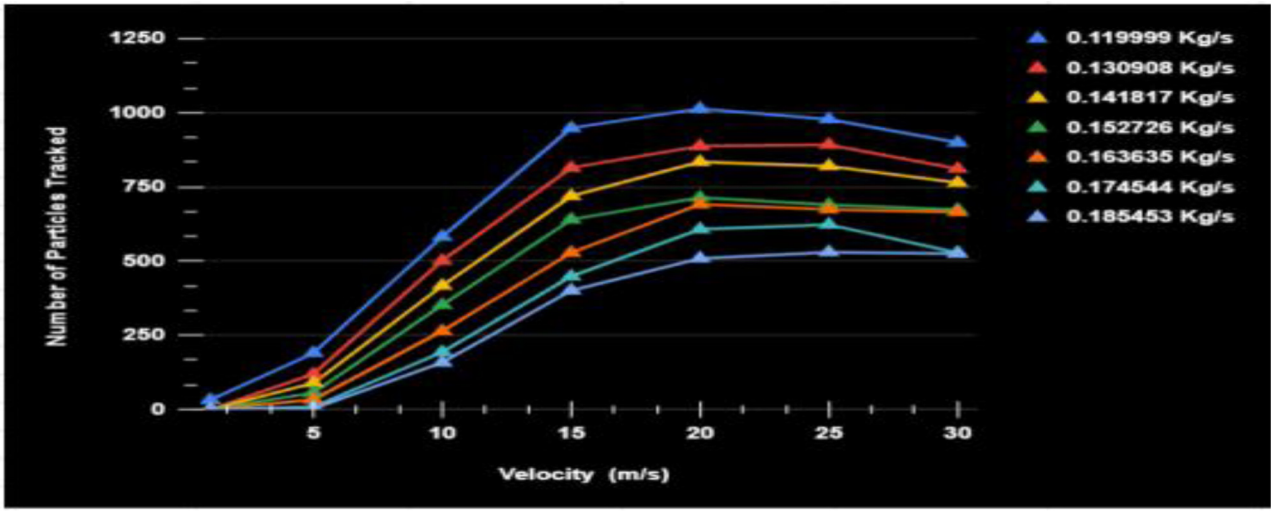

Fig. 11. Particles tracked at varying velocity.

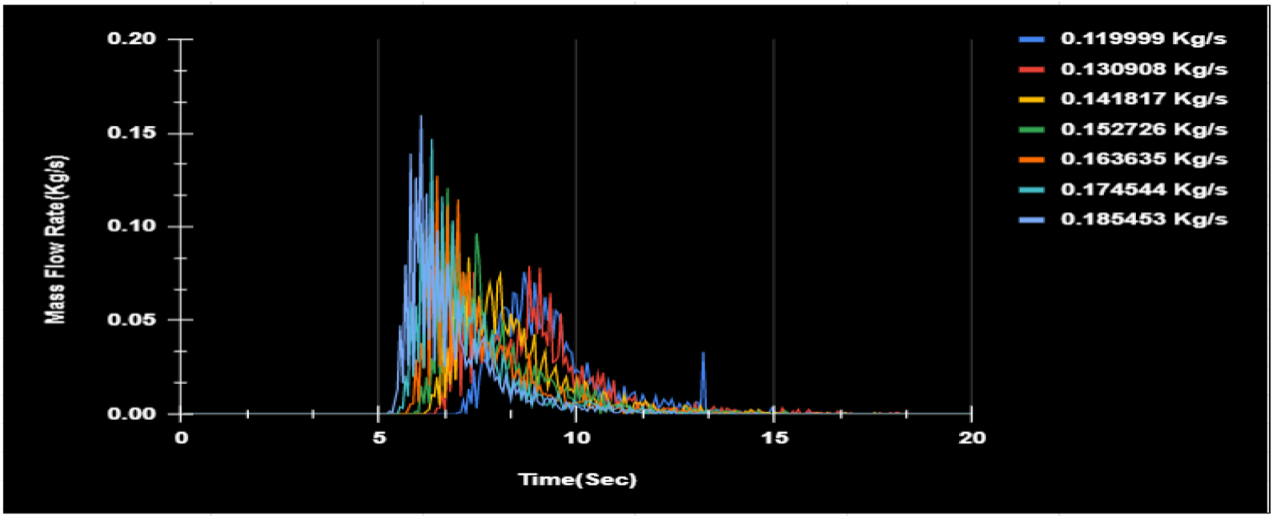

Fig. 12. Mass flow rate vs time at 1 m/s.

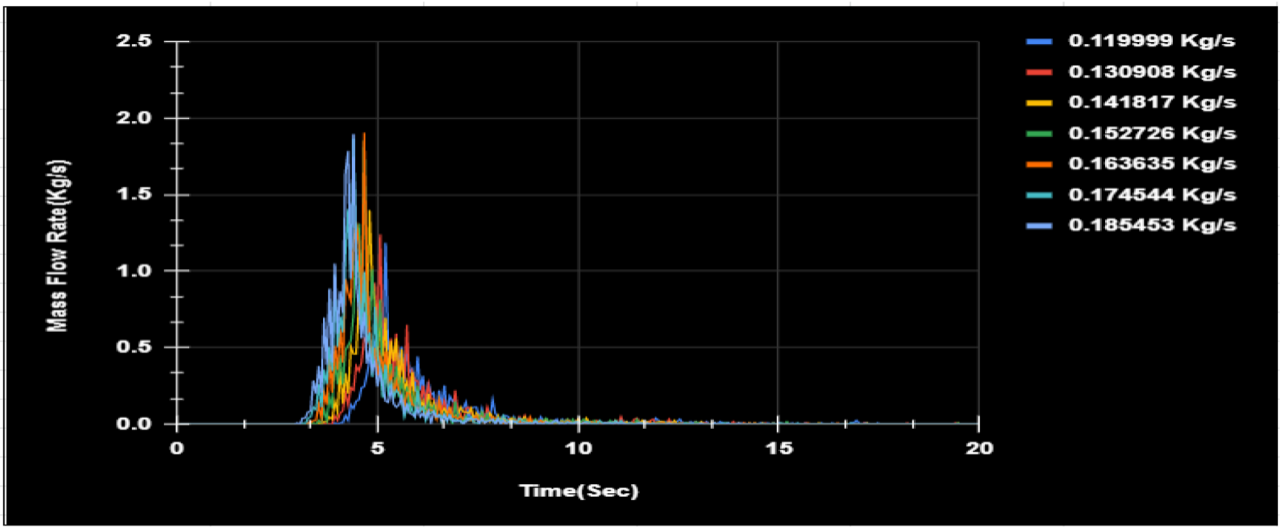

Fig. 13. Mass flow rate vs time at 10 m/s.

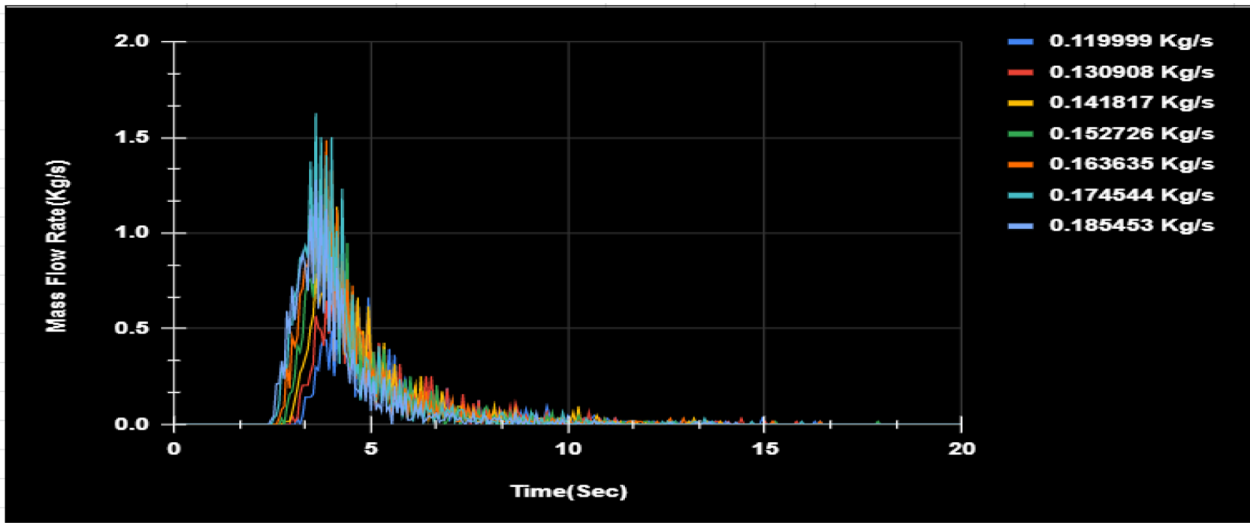

Fig. 14. Mass flow rate vs time at 20 m/s.

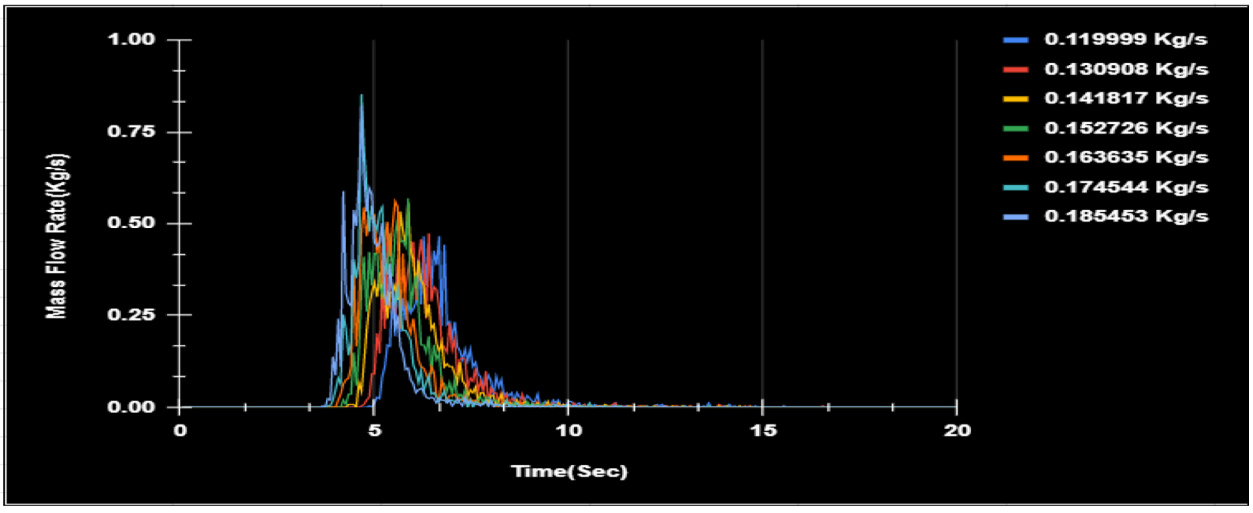

Fig. 15. Mass flow rate vs time at 5 m/s.

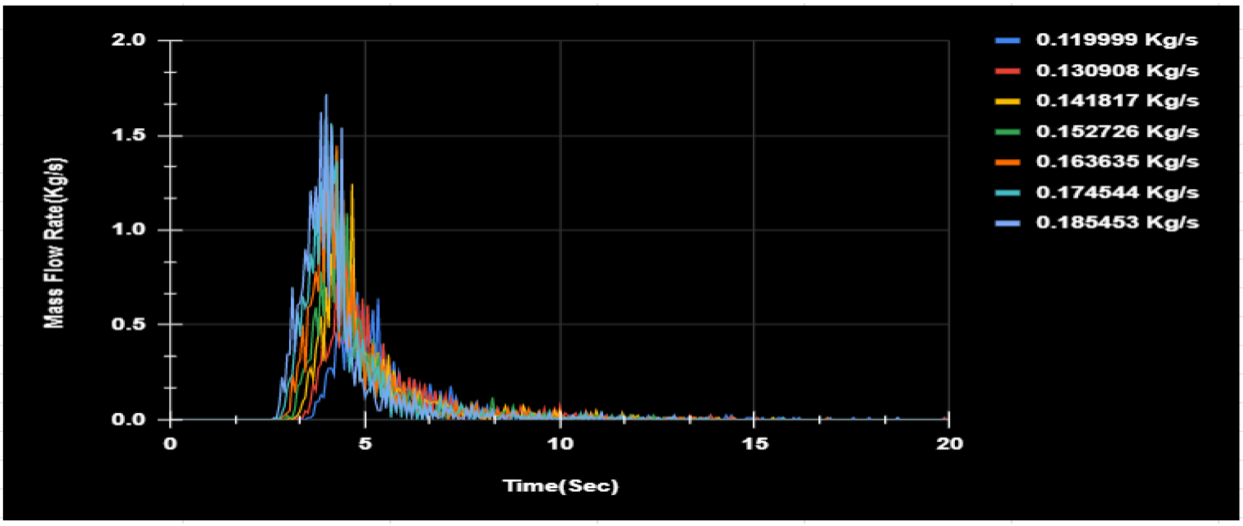

Fig. 16. Mass flow rate vs time at 15 m/s.

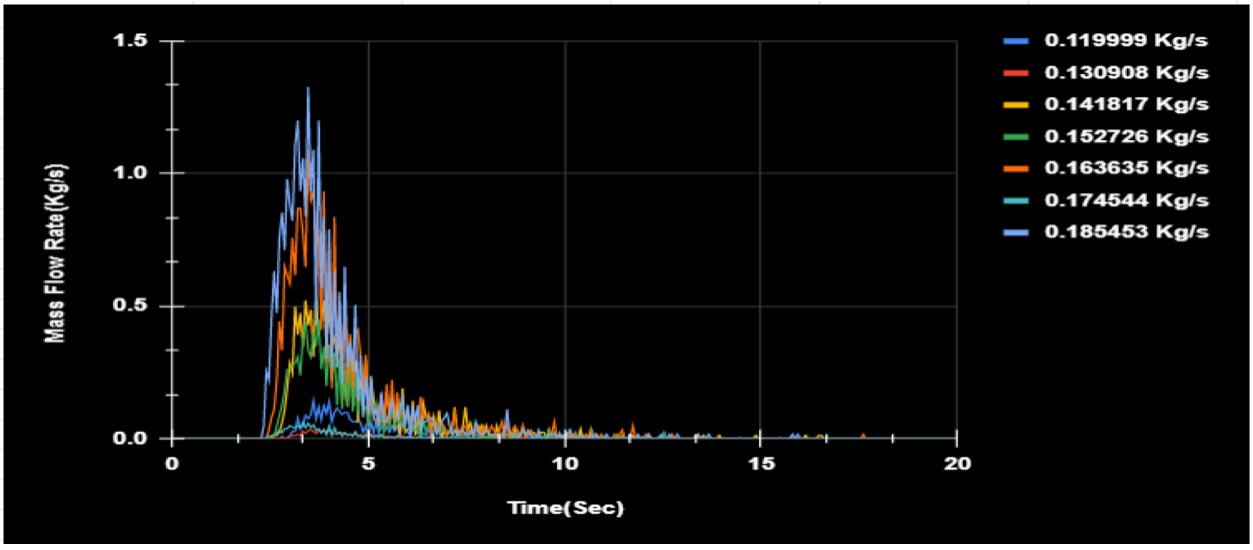

Fig. 17. Mass flow rate vs time @25m/s.

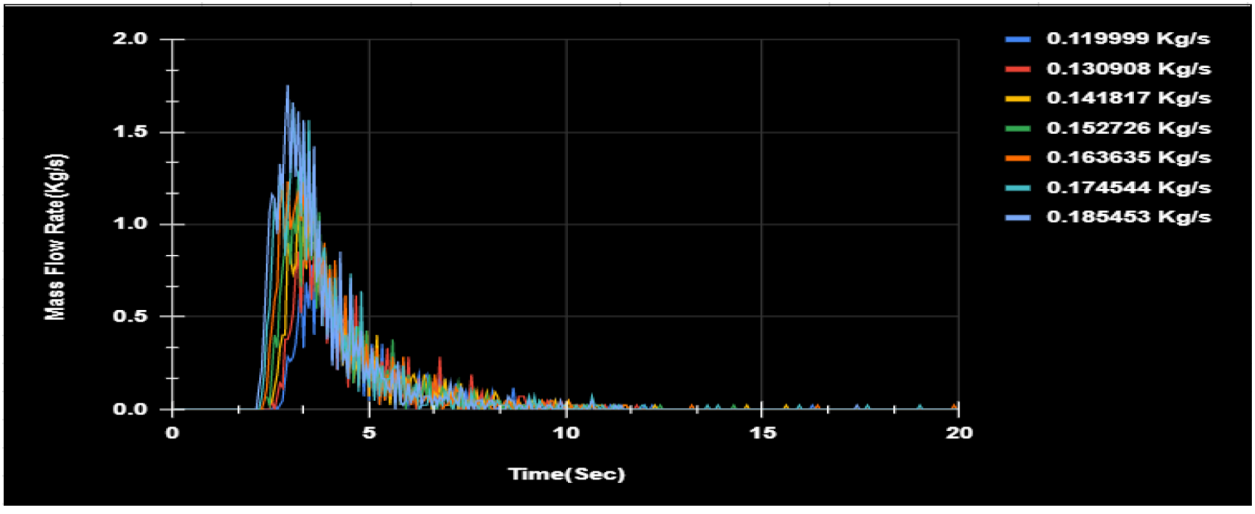

Fig. 18. Mass flow rate vs time @30m/s.

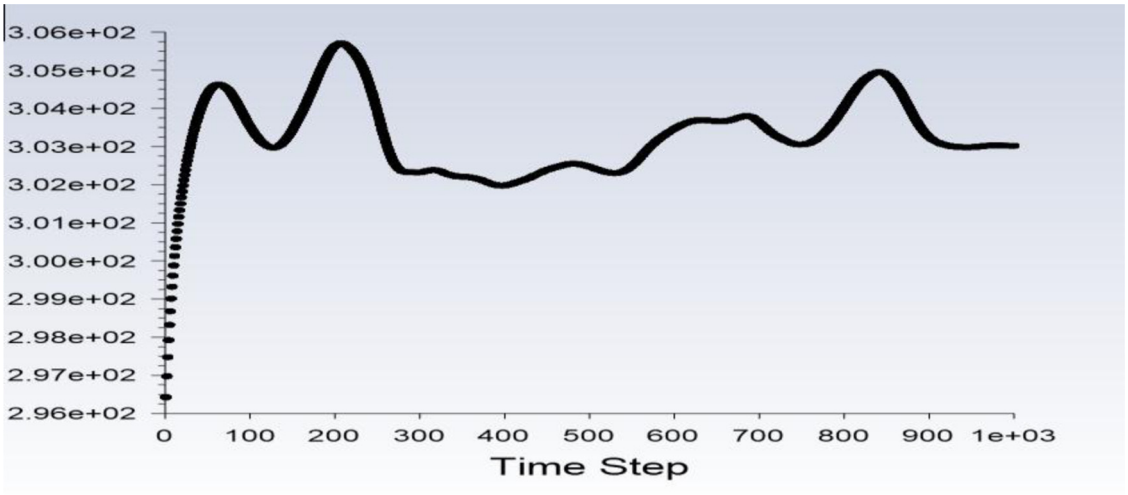

Fig. 19. Temperature variation of patient body.

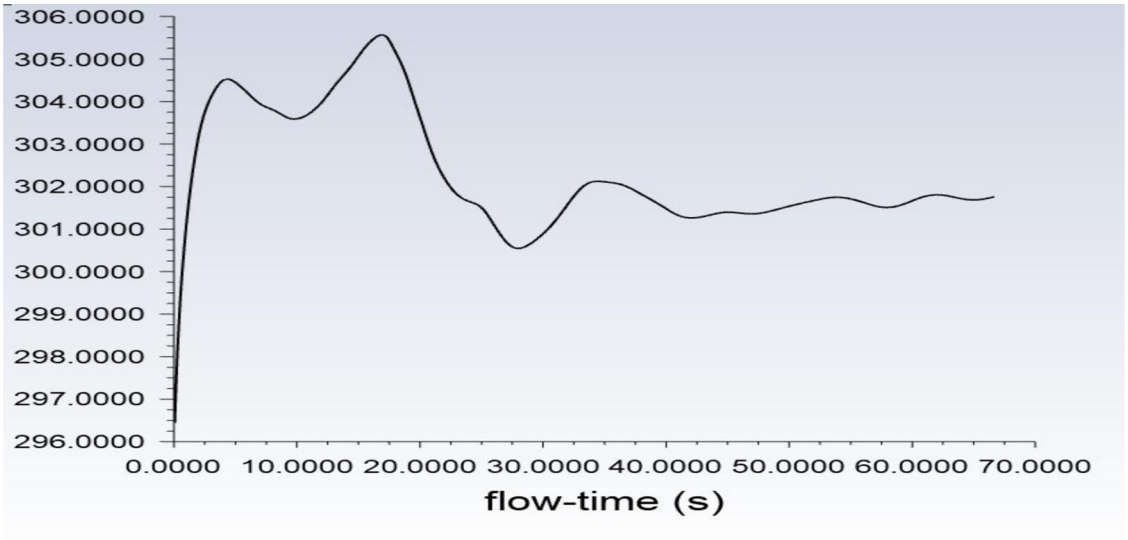

Fig. 20. Temperature variation of caretaker.

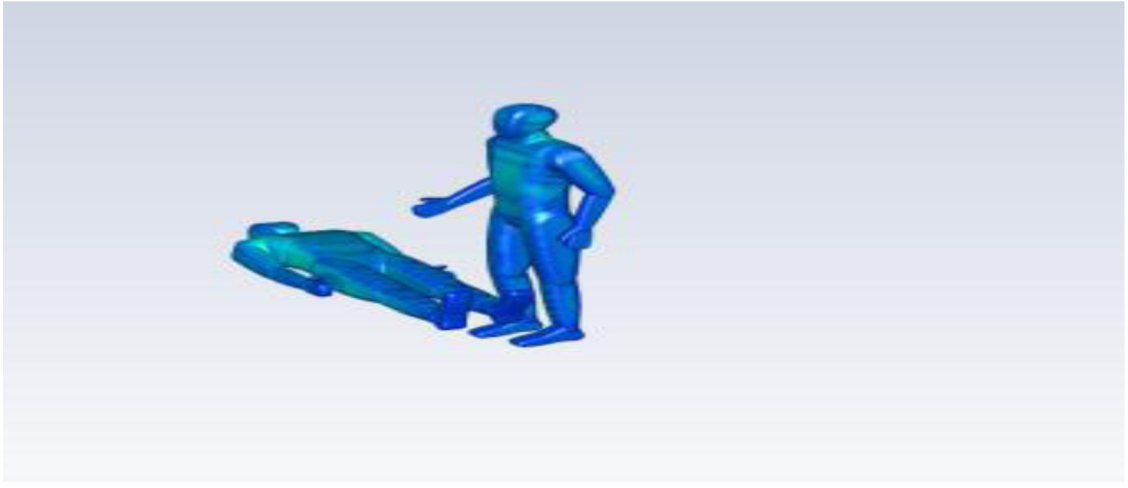

Fig. 21. Horizontal geometry: Patient. Vertical geometry: Caretaker.

Table 3. Particle tracking.

	Mass Flow (Kg/s)	0.119999		0.130908		0.141817		0.152726		0.163635		0.174544		0.185453	
Velocity (m/s)	Particle tracking	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	end
1		3198	32	3198	0	3198	0	3198	0	3198	0	3198	0	3198	0
5		3198	190	3198	119	3198	89	3198	56	3198	33	3198	8	3198	3
10		3198	582	3198	501	3198	417	3198	352	3198	264	3198	193	3198	158
15		3198	948	3198	814	3198	719	3198	640	3198	528	3198	448	3198	401
20		3198	1013	3198	887	3198	834	3198	714	3198	691	3198	607	3198	509
25		3198	978	3198	892	3198	820	3198	689	3198	674	3198	623	3198	530
30		3198	899	3198	811	3198	764	3198	673	3198	665	3198	528	3198	525

tained at 301.15 K which is significantly lesser than patient's body temperature, due to better airflow pattern around caretaker which has maintained his temperature to optimum level. Initially, a higher peak temperature was noticed because it takes a certain amount of time for cool air to circulate in a room which eventually as time progressed has reduced surface temperatures of both human geometries. Figures 19 to 21 would provide a better understanding of temperature distribution on both the geometries (patient and caretaker). As shown in Table 3 the particle count decreases gradually as the outlet mass flow rate increases.

6 Conclusions

These aerosol particles containing strains of virus possess a huge risk to humans especially in indoor facilities like health care centers, restaurants and various other concealed spaces. As it is necessary to have a proper ventilation system to be designed before building a space. Moreover, while designing a ventilation system various problem are related to the interaction of dispersed aerosol particles with environment, body inhalation and exhalation flow rate. So, having prior knowledge of aerosol particle generation and diffusion mechanisms is essential. Referring to has conducted experimental and CFD analysis to predict aerosol distribution, proving Computational Fluid Dynamics (CFD) simulations would provide a better understanding of such movements and interactions within a limited time compared to the experimental setup.

In this study, we have utilized the discrete phase model to analyze the flow simulations. The results obtained indicate that increasing the flow rate of the outlet ventilation system would reduce the injected contaminants in the room. Also, we have conducted simulation on the dispersion of particles from fixed positions whereas in other cases a patient might be lying down on a bed at a different position which might lead to a change in flow patterns. Hence, to provide optimal performance in removing these pathogens it is not preferable to change patient's position as recommended by the designer to another position. As per our conditions placing an outlet duct over the patient's head seems to work efficiently in removing contaminants. Moreover, this design has provided a better thermal comfort to both patient and caretaker in an isolation room has designed mathematical models to find the locations of particles produced from a cough has conducted both experimental and simulation setup with a personalized ventilation system to reduce the risk of infection. Similarly, these above results obtained from designed geometry at fixed positions could be useful in reducing virus diffusion at hospital wards, receptions, restaurants, etc.

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