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Original Article

A Computational Study of Hospital Isolation Room Environment to Assess the Spread of Airborne Contaminants

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Abstract

The safety of healthcare workers and patients in hospitals is a matter of paramount importance. Therefore, the significance of adequate ventilation in hospital rooms towards controlling airborne infections cannot be ignored. Although several reports discuss natural and mechanical ventilation in hospital isolation rooms, conflicting opinions recommend one ventilation method. There is also a paucity of information that relates engineering evaluation of hospital room ventilation to the design standards laid down by established public health agencies in the United States. This research aims to study hospital isolation room ventilation performance using natural and mechanical ventilation methods and assess certain guidelines on hospital room ventilation. Computational Fluid Dynamics is used to evaluate the concentration of contaminated air following a coughing event within a hospital isolation room using natural and mechanical ventilation. A novel technique employing a mechanical exhaust tube is proposed that may substantially reduce contaminant concentration. Within the same hospital isolation room, the normalized maximum concentration of contaminated air is much lower with two different mechanical ventilation methods (0.2% and 0.25%) than with the natural ventilation method (0.6%), suggesting that mechanical ventilation methods are more effective in reducing the concentration of contaminated air. In addition to established design parameters such as Air Change per Hour (ACH) and ventilation volume per patient, closer proximity to the vent from the contaminant source may also play a critical role in reducing contaminant concentration.

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1. Introduction

Airborne infections have been known to contribute significantly to the global disease burden. Typically, airborne infections can be classified as: (a) Obligate Airborne Transmission, where tiny airborne particles exclusively transmit the disease-carrying pathogen. A typical example of such an infection is tuberculosis. (b) Airborne transmission through inhalation occurs when infectious respiratory particles are inhaled from the air into the respiratory tract. Typical examples are influenza and COVID-19. (c) Preferential airborne transmission occurs where the pathogen can spread through multiple routes, but the most common is airborne transmission. A typical example of such an infection is measles [1]. Among the airborne infections, lower respiratory infections alone were responsible for approximately 2.6 million deaths globally in 2019 [2]. Similarly, in 2022, approximately 1.6 million deaths were caused globally by tuberculosis [3]. Perhaps the most significant episode of a global outbreak of an airborne disease was the COVID-19 pandemic, which caused enormous losses to human lives and economies worldwide. While more than 775 million people were infected by the virus worldwide, the disease also caused 7 million human fatalities. In the United States alone, as many as 103 million people were infected, and more than 1.2 million died from the disease [4]. A cohort study of hospitals in the United States revealed that approximately 5% of the COVID-19 cases were hospital-acquired [5]. Hospital-acquired infections (HAIs) have often been proven to be a persistent and difficult problem. It is estimated that among all HAIs, approximately a third involve airborne transmission at some point [6].

Although a comprehensive discussion of aerial dissemination in hospital rooms is beyond the scope of this research, the following is a discussion of the types of airborne diseases that predominantly cause nosocomial, or hospital-acquired infections (HAI). The Centers for Disease Control and Prevention (CDC) broadly categorizes HAIs as (a) ventilator-acquired pneumonia (VAP), (b) non-ventilator-acquired pneumonia (NVAP), and (c) lower respiratory tract infections such as bronchitis, tracheobronchitis, bronchiolitis, and tracheitis [7]. Based on a point prevalence survey conducted in the United States in 2015, it was reported that pneumonia was the most common HAI in acute hospital settings [8]. In addition, as compared to HAIs that spread through contact, airborne HAIs are harder to control [9].

During the COVID-19 pandemic, many superspreading events were attributed to nosocomial point sources. For instance, in Hong Kong, a superspreading event involved 9 healthcare workers and 12 patients and occurred within 9 days in 3 out of 6 cubicles where no air exhaust was built [10]. Another study suggested that the hospital-acquired COVID-19 infections during the Omicron virus period were also associated with high mortality among patients with good vaccine coverage [11]. Several articles have suggested that adequate hospital room ventilation is the key to reducing nosocomial airborne diseases [12-14]. Therefore, assessing the spread of airborne pathogens using different ventilation methods in a hospital isolation room is important.

Ventilation moves outdoor air into a hospital room. It is distributed inside, intending to provide healthier air by diluting the pollutants inside the room and removing the infected air through the exhaust [15]. Two general ventilation methods may be used in a hospital room: (a) natural ventilation, and (b) mechanical ventilation. Natural ventilation uses natural forces such as winds and thermal buoyancy forces due to the density differences between indoor and outdoor air. Therefore, natural forces drive outdoor air through purpose-built openings such as ventilators, windows, and doors [16]. Mechanical ventilation involves mechanical devices such as fans and air conditioners to achieve the purpose of ventilation. Computational Fluid Dynamics (CFD) is a state-of-the-art engineering tool, which is also an inexpensive, safe method of assessing ventilation efficiency in a hospital isolation room. CFD has been widely used for air-flow studies in various public places [17-19].

However, fewer articles reported CFD results showing bioaerosol concentration based on ventilation strategies [20,21]. Besides, although various researchers have studied hospital isolation room ventilation using natural and mechanical means, conflicting reports recommend one ventilation method over another. For instance, a research group in a comprehensive review of several articles suggested that the mean total bioaerosol concentration in hospitals was the maximum in areas of natural ventilation and significantly lower in mechanical ventilation [22]. On the other hand, another research group emphasized that the most common and appropriate ventilation solution in patient rooms is natural ventilation through open windows [23]. In addition, natural ventilation systems are sometimes preferred because they are relatively inexpensive to install and maintain [24]. Finally, the current body of knowledge lacks reports that connect engineering evaluations of hospital isolation room ventilation to the current institutional design policies associated with ventilation in the United States. Therefore, the present research evaluates the effectiveness of hospital isolation room ventilation using natural and mechanical means and, based on the results obtained, assesses the current hospital isolation room design policies in the United States. This work uses computational fluid dynamics (CFD) to study airflow and the concentration of contaminated air in an isolation room of a hospital following a coughing or sneezing event by a patient. The infected air concentration is evaluated with time for three different ventilation strategies within a hospital isolation room.

To the best of our knowledge, this is the only article that uses CFD to assess the effectiveness of natural ventilation against mechanical ventilation in a hospital isolation room. It also subsequently considers the current institutional ventilation policies in healthcare administration in the United States. The paper also presents a novel ventilation technique using a mechanical exhaust tube that may yield enhanced ventilation in hospital isolation rooms.

2. Materials and Methods

The following are the details of the hospital isolation room configurations that are evaluated:

a) Configuration # 1: Hospital Isolation Room with Natural Ventilation
The hospital isolation room has a length of 6m, a width of 3m, and a height of 3m. The bed has a length of 2m and a width of 1 m. The height of the bed is 0.6 m. The isolation room has a fan blower located at the center of the ceiling with a diameter of 0.7 m. The south side wall of the room has a ventilator with dimensions of 1 m × 0.2 m × 0.1 m. This room has no mechanical exhaust and completely depends on natural ventilation. Fig. 1 shows the simulation geometry for configuration # 1.

b) Configuration # 2a: Hospital Isolation Room with Mechanical Ventilation
In this configuration, the dimensions of the isolation room, the bed, pillow, and the ceiling fan blower unit are the same as configuration #1. The ventilator on the south side wall is replaced by a mechanical exhaust tube, which is located 0.4 m above the mouth of the patient, with their head on the pillow. The diameter of the tube is 0.25 m, and its length is 2 m. This configuration of the isolation room solely relies on the mechanical ventilation offered by the exhaust tube. Fig. 2 shows the simulation geometry.

c) Configuration # 2b: Hospital Isolation Room with Mechanical Ventilation
In this configuration, the room, bed, and pillow dimensions are the same as the previous configurations. Like configuration #2a, it also has the mechanical exhaust tube. Finally, it has an additional fan blower unit on the room's north side wall near the patient's bed. Both fan blower units have diameters of 0.5m. Fig. 3 shows the simulation geometry for configuration #2b.

CFD simulations are performed using the commercial code, ANSYS Fluent 18.2, to evaluate the concentration of the contaminant inside a hospital room after a coughing incident by the patient [25]. The coughing or sneezing of the patient on the bed is modeled as a sudden high-velocity jet of contaminated air at time $t = 0$, with a flow rate of approximately 4.5 L/s, lasting for 0.1 seconds. The RNG k-ε turbulent model is used for transient simulations. The species equation governs the transportation of the airborne pathogen. The CFD code solves the Navier-Stokes Equations in 3 dimensions, in addition to the continuity and species equations, which are shown by Eqs. (1) – (5):

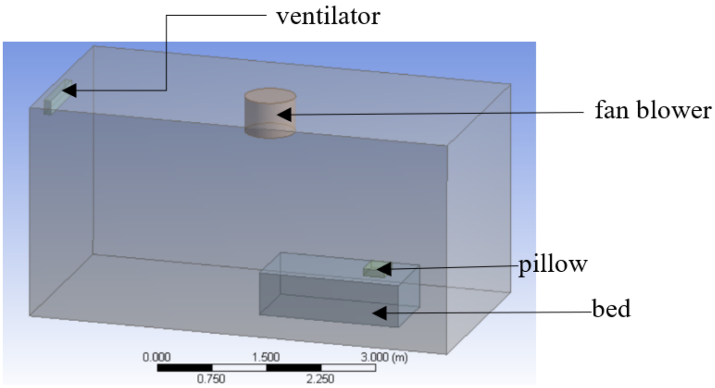

Fig. 1: Configuration # 1 showing hospital room with natural ventilation.

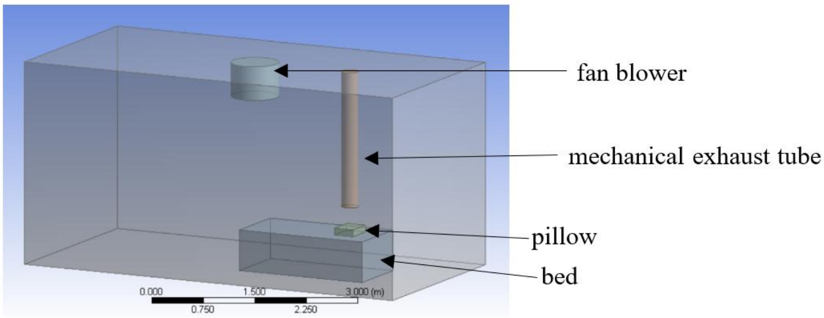

Fig. 2: Configuration # 2a showing hospital room with mechanical ventilation.

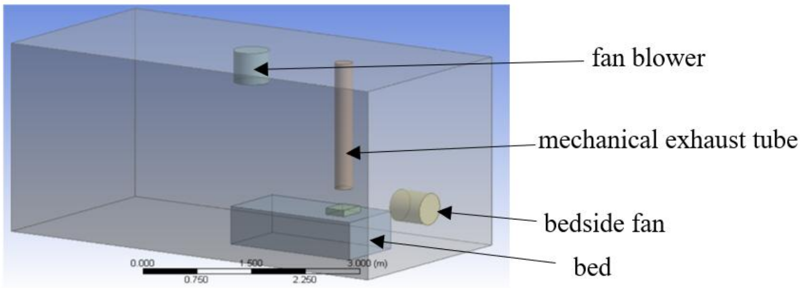

Fig. 3: Configuration # 2b showing hospital room with mechanical ventilation.

Continuity or Mass Conservation Equation

$$\frac{\partial \rho}{\partial t} + \Delta(\rho U) = 0 \tag{1}$$

where ρ is the density of the fluid and U is the velocity of the fluid.

Momentum Equation

$$\frac{\partial}{\partial t}(\rho U) + \nabla(\rho U \times U) = -\nabla P' + \nabla\left[\mu_{eff} \nabla U + (\nabla U)^T\right] \tag{2}$$

where P' is the modified pressure, and μ_{eff} is the effective viscosity.

$$P' = P + \frac{2}{3}\rho k + \left(\frac{2}{3}\mu_{eff} - \xi\right)\nabla U \tag{3}$$

where ξ is the bulk viscosity, and k is the turbulent intensity.

$$\mu_{eff} = \mu + \mu_T \tag{4}$$

where μ_T is the turbulent viscosity.

Species Equation

$$\frac{\partial}{\partial t}(\rho\Phi) + \nabla\left(\rho U \Phi - \Gamma_{eff}\nabla\Phi\right) = S \tag{5}$$

where Φ is the mass fraction of gaseous species, Γ_{eff} is the effective diffusivity, and S is the rate of creation by addition from the dispersed phase.

The RNG k-ε turbulence model is used for the simulations. This model is often used for low Reynolds number turbulent flows, including transitional flows. Also, it is often preferred for studying indoor air-flow characteristics [26,27]. Eq. (6) shows the RNG k-ε model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho_\varepsilon - Y_M + S_k \tag{6}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \tag{7}$$

where G_k represents the generation of turbulence kinetic energy due to mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy, Y_M is the contribution of fluctuating dilatation in compressible turbulence to the overall dissipation rate, and α_k and α_ε are the inverse effective Prandtl numbers for k and ε respectively [25].

In addition, the Discrete Phase Model (DPM) is used to model particle dispersion, such as droplets from the patient's mouth following the coughing event. This model is used to simulate particle or droplet behavior within a continuous fluid phase. The discrete phase concentration is calculated using Eq. (8):

$$C = \frac{\overline{m_{p,cell}}}{v_{cell}} \cdot t_p \cdot \frac{\dot{m}_{p,cell}}{m_p} \tag{8}$$

where C is the DPM concentration, $\overline{m_{p,cell}}$ is the average particle mass in a cell, v_{cell} is the cell volume, t_p is the particle residence time, $\dot{m}_{p,cell}$ is the total particle mass flow rate, and m_p is the average mass of a single particle.

The pressure-velocity coupling is performed using the SIMPLE algorithm. Transient simulations are performed to study the spread of contaminated air following a coughing event by the patient on the bed through 10 s. The coughing is assumed to be a short burst that elapses through 0.1 s. Therefore, the time-step size chosen for the simulations is 0.01 s, as it is a tenth of the time elapsed through the coughing event by the patient. The number of time steps is 1000 for a total duration of 10 s. Table 1 shows the boundary conditions used for the three configurations.

A tetrahedral mesh was used for simulations. To obtain mesh independence, the pressure inside the hospital room was computed as a function of the mesh size. The mesh independence was obtained with approximately 4.09 million mesh elements. Fig. 4 shows the mesh independence test result.

Table 1: Boundary conditions used in simulations.

Boundary Conditions	Configuration #1	Configuration #2a	Configuration #2b
Velocity Inlet	• Fan Blower Inlet	• Fan Blower Inlet • Mechanical Exhaust Tube Inlet	• Fan Blower Inlet • Mechanical Exhaust Tube Inlet • Bedside Fan Inlet
Pressure Outlet	• Fan Blower Outlet • Ventilator Outlet	• Fan Blower Outlet • Mechanical Exhaust Tube Outlet	• Fan Blower Outlet • Mechanical Exhaust Tube Outlet • Bedside Fan Outlet
DPM Boundary	• Pillow Top	• Pillow Top	• Pillow Top

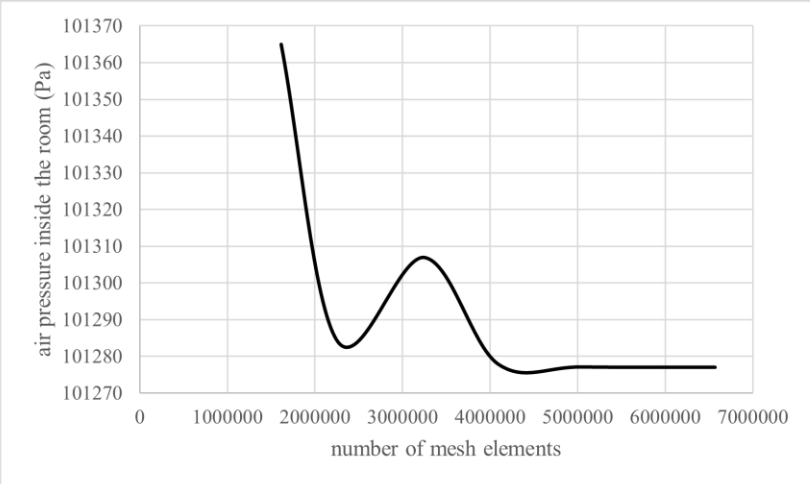

Fig. 4: Mesh independence test.

3. Results and Discussion

Transient CFD simulations are performed to study the normalized maximum concentration of contaminated air 10 seconds after the coughing event by the patient. To study the dispersion of polluted air inside the hospital room, the particle pathlines within the plane parallel to the length, and through the center of the room, are studied. Fig. 5 shows the pathlines after 9 s following the coughing event in hospital room configuration # 1. The location of the bed and the region south of the center of the room have many pathlines, suggesting a high density of contaminated air in this region. This indicates that with natural ventilation, even after 9 s from the coughing event, these areas have a significant amount of contaminated air. The initial pathlines with IDs ranging from 0 to 9.45×10^3 are directed towards the south side of the room.

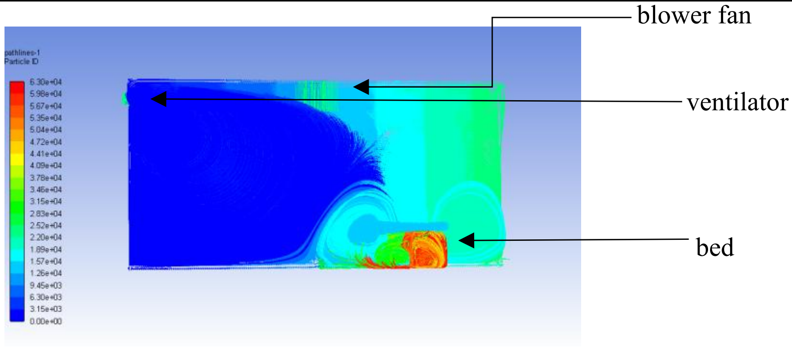

Fig. 5: Particle pathlines in hospital room configuration # 1.

Fig. 6 shows the particle pathlines after 9 s in hospital room configuration # 2a. In this configuration, the ventilator is replaced by the mechanical exhaust tube. The fan blower from the ceiling remains in its location. The mechanical exhaust tube reduces the number of pathlines near the bed. A lesser number of pathlines, ranging between 0 and 8.19×10^3, are directed towards the south side of the room. In addition, a significant number of pathlines pass along the mechanical exhaust tube, which suggests its effectiveness.

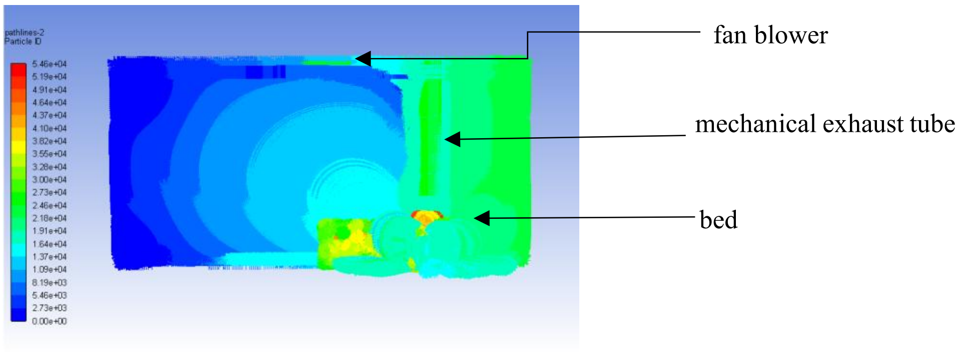

Fig. 6: Particle pathlines in hospital room configuration # 2a.

Fig. 7 shows the particle pathlines, 9 s after the coughing event in the hospital room configuration # 2b. In this configuration, besides the blower fan from the ceiling, there is a bedside fan on the northside wall. The pathline profile of contaminated air after the coughing event is comparable to configuration # 2a. However, the number of pathlines of contaminated air in the zone near the bed is slightly less than configuration # 2a.

Since the source of contamination is the patient's mouth resting on the pillow on the bed and pointing upwards, the concentration of contaminated air is studied in the zone near the pillow and the bed. Figs. 8 and 9 show the concentration of contaminated air after 1 s and 9 s, respectively, in configuration #1.

Figs. 10 and 11 show contaminant concentration in the vicinity of the pillow after 1 s and 9 s, respectively, from the start in configuration #2a. Compared to configuration #1, the concentration of contaminants decreases more in configuration #2a.

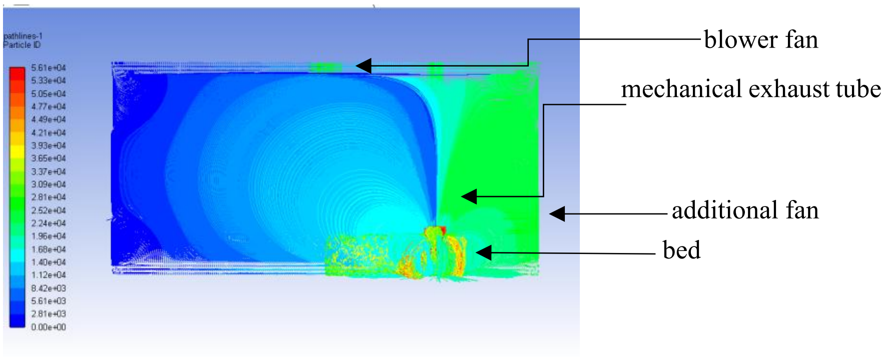

Fig. 7: Particle pathlines in hospital room configuration # 2b.

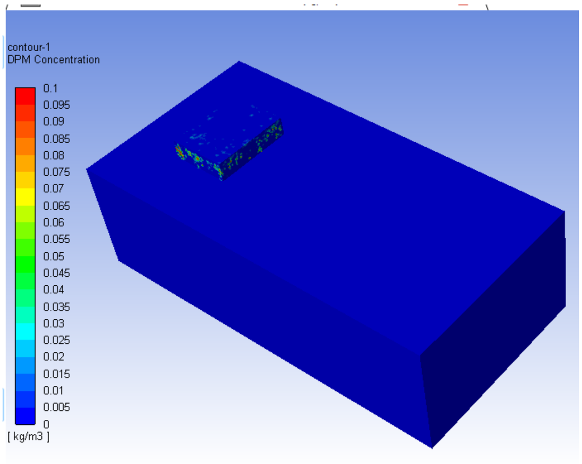

Fig. 8: Particle concentration near the bed in configuration #1 – 1 s.

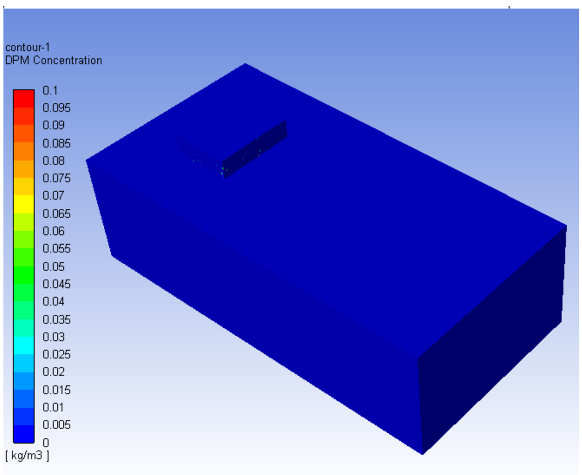

Fig. 9: Particle concentration near the bed in configuration #1 – 9 s.

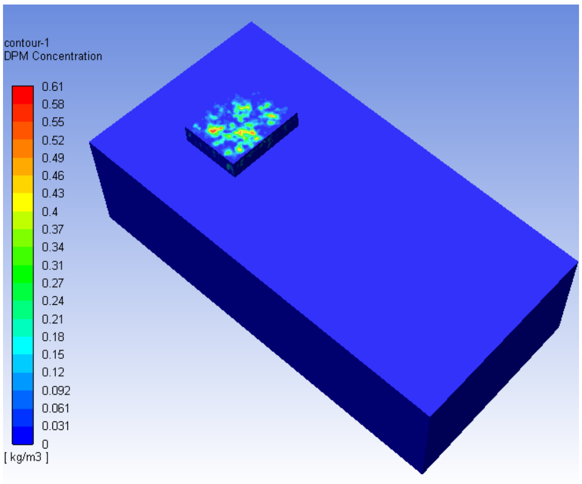

Fig. 10: Particle concentration near the bed in configuration #2a – 1 s.

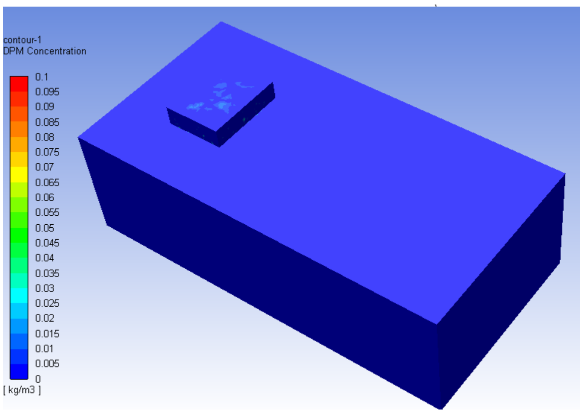

Fig. 11: Particle concentration near the bed in configuration #2a – 9 s.

Figs. 12 and 13 show the contaminant concentration in the vicinity of the bed after 1 s and 9 s, respectively, in configuration #2b. Like configuration #2a, the contaminant concentration decreases significantly after 9 s in configuration #2b.

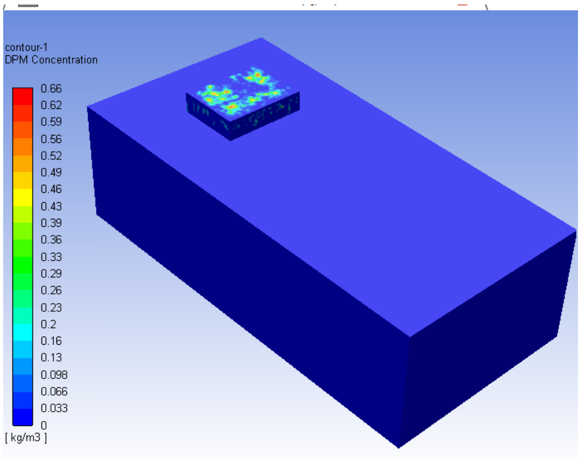

Fig. 12: Particle concentration near the bed in configuration #2b – 1 s.

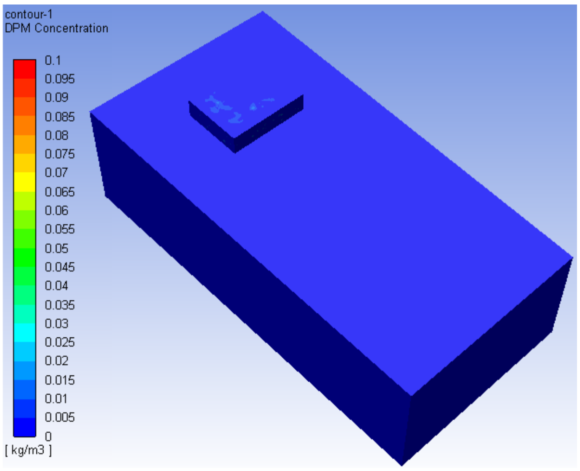

Fig. 13: Particle concentration near the bed in configuration #2b – 9 s.

Figs. 14, 15, and 16 show the pressure profile after 9 s from the coughing event within configurations #1, #2a, and #2b, respectively. The results show that the pressure within the hospital room is slightly less than atmospheric pressure with the mechanical exhaust tube in both configurations #2a and #2b.

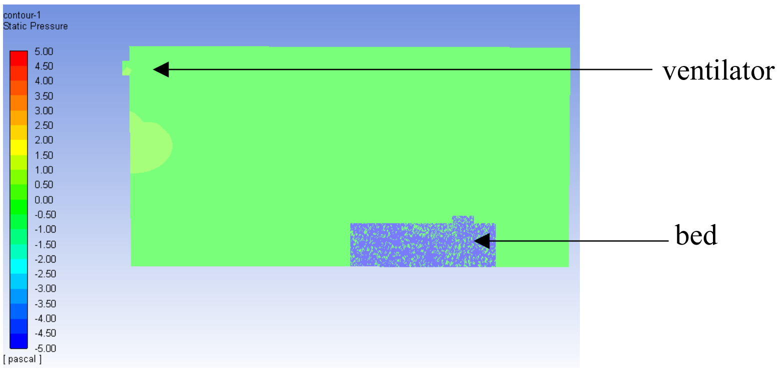

Fig. 14: Pressure profile in configuration #1 – 9 s.

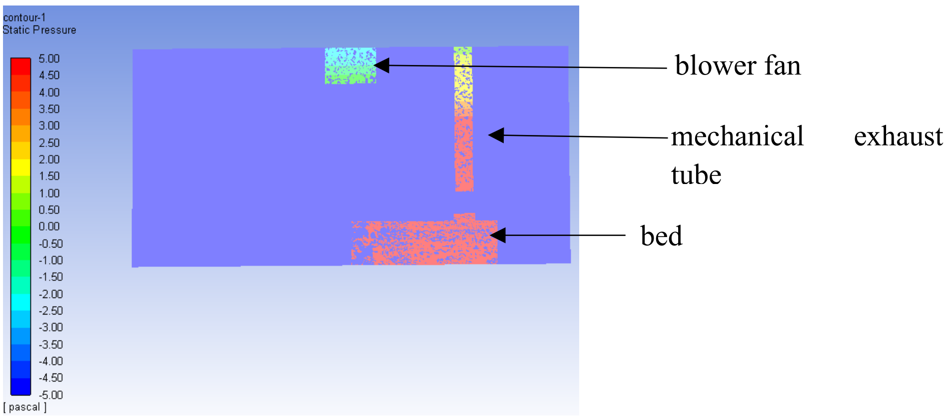

Fig. 15: Pressure profile in configuration #2a – 9 s.

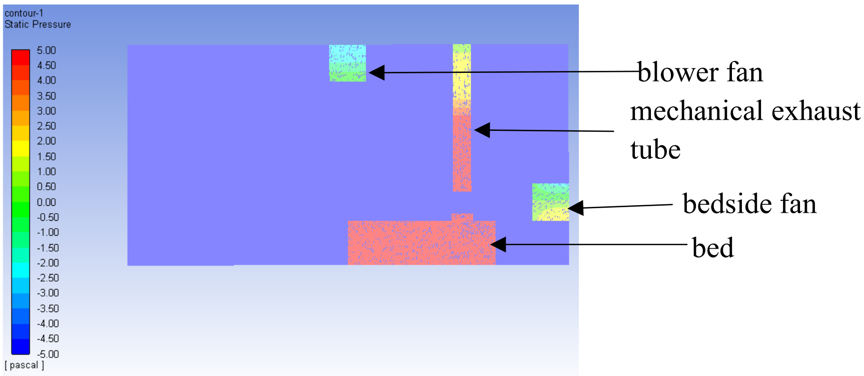

Fig. 16: Pressure profile in configuration #2b – 9 s.

The normalized maximum concentration of contaminated air at each second is evaluated for the three configurations of the hospital isolation room. Normalized concentration is defined using Eq. (9) [21]:

$$C_{normalized} = \frac{C_{\max i}}{C_{\max}} \tag{9}$$

where $C_{normalized}$ is the normalized concentration, $C_{\max i}$ is the maximum concentration at a given time, i, and $C_{\max}$ is the overall maximum concentration of the contaminant inside the hospital isolation room, immediately after the coughing event.

3.1. Assessment of the effectiveness of simulated ventilation methods

Fig. 17 shows all configurations' normalized maximum concentration of infected air through 10 seconds from the coughing event. Results show that among the three configurations evaluated, the normalized maximum concentration reduces to a minimum with mechanical configuration #2b, two blower units, and the mechanical exhaust tube.

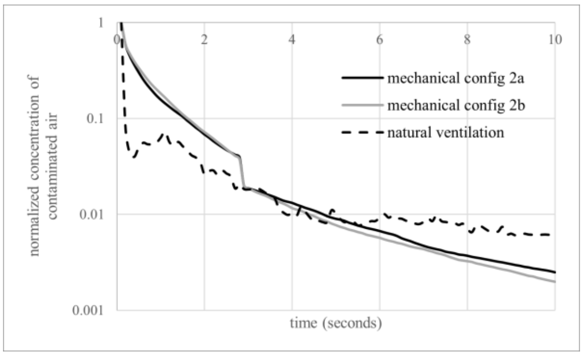

Fig. 17: Normalized concentration of contaminated air for all configurations.

Also, the normalized maximum concentration marginally improves while using mechanical ventilation #2b from mechanical ventilation #2a, suggesting that the additional blower unit does not significantly improve ventilation in the isolation room. Fig. 17 shows that the normalized maximum concentration is much higher with natural ventilation than with mechanical ventilation, 10 seconds after the coughing incident.

While using the natural ventilation system, the normalized maximum concentration drops to less than 0.1 in approximately 0.2 seconds. On the other hand, using both mechanical ventilation systems, it takes approximately 1.5 seconds to reduce the concentration of contaminated air to the same level.

However, compared to the natural ventilation system, both mechanical ventilation systems facilitate a steeper drop of normalized maximum concentration of contaminated air after approximately 6 seconds.

Configuration #2a-mechanical ventilation system can be compared against the work reported by previous researchers who used a similar mechanical exhaust tube and performed numerical simulations to evaluate the normalized maximum concentration of contaminated air in a hospital triage room [21]. The dimensions of the hospital triage room were the same as those of the isolation room in the present work. They evaluated the effectiveness of the placement of the mechanical exhaust tube, or the 'hood' as they referred to it, within the room, towards improving ventilation and reducing the normalized concentration of contaminated air after a coughing episode. They obtained the normalized concentration of contaminated air using two plans, where the mechanical exhaust tube originated from the ceiling and the wall near the patient bed, respectively. The mechanical exhaust tube from the ceiling was 40 cm above the bed. The normalized concentration of the contaminated air was reduced to approximately 0.01 in 4 seconds. In the present work, configurations #2a and #2b employ the mechanical exhaust tube originating from the ceiling and extending 40 cm above the bed. Using configuration #2a, the normalized concentration of contaminated air reduces to 0.013 in 4 seconds, which is in reasonable agreement with the work by previous researchers [21].

Configurations #2a and #2b, simulated in this work, can be categorized as mixed mechanical ventilation methods. In this method, the diffuser is typically located in the ceiling and delivers air at moderately high speeds to promote mixing [28]. Some studies suggested that in typical mixed mechanical ventilation methods, such as configuration #2a in this research, low supply and high-exhaust in proximity may yield significant contaminant removal [29-31]. The results from this research agree with these findings as configurations #2a and #2b employ the mechanical exhaust tube strategically placed above the patient's mouth. Contrary to the results reported in this work, Qian et al. reported that natural ventilation could achieve high ventilation rates. However, they recommended keeping both doors and windows open in a hospital ward [14].

Among the other parameters governing the performance of ventilation systems in hospital isolation rooms are: (a) Air Changes per Hour (ACH), and (b) Ventilation Volume per Patient.

ACH is evaluated using Eq. (10):

$$ACH = \frac{600Q}{\forall} \tag{10}$$

where ACH is the air change rate per hour, Q is the volumetric flow rate in cubic feet per minute, and $\forall$ is the volume of the hospital isolation room in cubic feet. In the present work, ACH with mechanical ventilation is evaluated as approximately 9.75 per hour, while it is approximately 1.14 per hour with natural ventilation. In addition, the ventilation rate per patient with mechanical ventilation systems is 146 l/s, while it is approximately 17.1 L/s using the natural ventilation system.

In configuration #2a with the mechanical ventilation system, the normalized maximum concentration of contaminated air reduces to 0.0025 (0.25%) after 10 seconds, while it reduces to 0.0020 (0.20%) after 10 seconds in configuration #2b with a similar mechanical ventilation system. On the other hand, in configuration #1 with the natural ventilation system, the normalized maximum concentration reduces to 0.006 (0.60%) in 10 seconds. Therefore, as ACH and the volume flowrate per patient within the hospital isolation room increase by almost 9 times from configuration #1 to configuration #2a, the normalized maximum concentration of contaminated air reduces by approximately 67%.

3.2. Evaluation of Current Policies on Hospital Ventilation

Currently, hospital room ventilation guidelines in the United States are laid down by several organizations such as the World Health Organization (WHO), the Centers for Disease Control and Prevention (CDC), the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), and the American Institute of Architects (AIA). Two of the most important parameters for ventilation assessment in hospital isolation wards are Air Change Rate (ACH), and ventilation volume per patient. Table 2 shows the various guidelines that govern the ventilation of isolation ward spaces in the United States:

Table 2: Guidelines governing ventilation policies of isolation ward spaces in the United States

Governing Organization	Minimum ACH	Ventilation Volume per Patient (l/s) for a 4 x 2 x 3 m^3 room
WHO	$\geq$ 12	$\geq$ 80
CDC	$\geq$ 12 for new facilities $\geq$ 6 for existing facilities	$\geq$ 56
AIA	$\geq$ 6	$\geq$ 40
ASHRAE	$\geq$ 6	$\geq$ 40

WHO defines a room with ACH $\geq$ 12 as an airborne precaution room, which can be naturally or mechanically ventilated. The airborne precaution room is equivalent to the airborne infection isolation room as defined by CDC. Likewise, for new facilities, CDC recommends a minimum ACH of 12 using medical grade filters. Also, both AIA and ASHRAE recommend a minimum total ACH of 6.

Based on the results obtained in the present research, it is observed that the increase in ACH from configuration # 1 to configuration #2a and configuration #2b correlates with the decrease in normalized maximum concentration of contaminated air in the hospital isolation ward. The hospital isolation ward simulated in this work accommodates a single patient and the results also show that the normalized maximum concentration of contaminated air reduces with an increase in ventilation volume per patient. In addition, simulation results show that normalized maximum concentration of contaminated air increases with the increase in distance between the contaminant source and the outlet within the isolation ward. For instance, in configuration #2a and #2b, the mechanical exhaust tube is located 40 cm above the contaminant source, which is the mouth of the patient. However, in configuration #1, the ventilator outlet is located approximately 6.2 m away from the patient's mouth. Therefore, the results suggest that the distance between the contaminant source and the vent is also an important parameter governing the ventilation performance of a hospital isolation ward. It is therefore proposed that the ventilation guidelines also account for the location of the potential contaminant source and its distance from the vent or outlet.

4. Conclusion

This study reports a novel methodology where a strategically placed mechanical exhaust tube near the patient in a hospital isolation room can significantly reduce airborne contamination. The results show that among the three configurations of a hospital isolation room studied, the normalized maximum concentration of contaminated air reduces to a minimum of approximately 0.25% with a mechanical ventilation system that includes a blower unit from the ceiling and the proposed mechanical exhaust tube, 40 cm above the patient's mouth on the pillow. When an additional bedside blower unit is used, the normalized maximum concentration marginally improves to approximately 0.20%. This suggests that an extra source of air inlet within the room does not significantly enhance ventilation performance. Also, through the first half second, the concentration of contaminated air reduces faster when natural ventilation is used. In addition, for approximately 5 seconds, the concentration of contaminated air keeps reducing, after which mechanical ventilation proves more efficient. The CFD results obtained from this study support previously reported results that suggest mechanical ventilation facilitates improved ventilation performance through reduced concentration of contaminated air within the room. Although the non-availability of an experimental validation limits this study, the results suggest a hypothesis that, in addition to ACH and ventilation volume per patient, the ventilation performance is a function of the distance between the contaminant source and the vent outlet within the room. The study also suggests that a mechanical exhaust tube closer to the patient's mouth in an isolation room may help lessen the concentration of contaminated air. Furthermore, the outcomes from this research call for additional investigations to assess the ventilation performance with additional ventilation outlets from a hospital isolation room.

Declaration of Conflict of Interest

The authors declared no conflict of interest with any other party on the publication of the current work.

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References

[1] J. Kutter, M. Spronken, P. Fraaij, R. Fouchier, and S. Herfst, Transmission Routes of Respiratory Viruses among Humans, Current Opinion in Virology. 28 (2018) 142–151. https://doi.org/10.1016/j.coviro.2018.01.001
[2] Our World in Data, Death Rate from Infectious Diseases, 2024. https://ourworldindata.org/grapher/infectious-disease-death-rates?tab=chart
[3] Center for Disease Control and Prevention. Respiratory Illnesses Data Channel, 2024. https://www.cdc.gov/respiratory-viruses/data/index.html
[4] World COVID-19 Dashboard, World Health Organization Data, 2024. https://data.who.int/dashboards/covid19/deaths?n=o (accessed 31 July 2024).
[5] K.M. Hatfield, J. Baggs, A. Maillis, S. Warner, J.A. Jernigan, S.S. Kadri, M. Klompas, and S. Reddy, Assessment of Hospital-Onset SARS-CoV-2 Infection Rates and Testing Practices in the US, 2020-2022, JAMA Network Open. 6.8 (2023) e2329441-e2329441. https://doi.org/10.1001/jamanetworkopen.2023.29441
[6] W.J. Kowalski. Air-Treatment Systems for Controlling Hospital-Acquired Infections. HPAC Engineering. 1 (2007) 2-22.
[7] A. Sikora, and F. Zahra, Nosocomial infections, StatPearls Publishing LLC, 2020.

[8] S.S. Magill, E. O'Leary, S. J. Janelle, D. L. Thompson, G. Dumyati, J. Nadle, ... J. R. Edwards, Emerging Infections Program Hospital Prevalence Survey Team. Changes in prevalence of health care-associated infections in US hospitals, The New England Journal of Medicine. 379.18 (2018) 1732-1744. https://doi.org/10.1056/NEJMoa1801550

[9] I. Eames, J.W. Tang, Y. Li, and P. Wilson, Airborne Transmission of Disease in Hospitals, Journal of the Royal Society Interface. 6 (2009) S697-S702. https://doi.org/10.1098/rsif.2009.0407.focus

[10] V.C. Cheng, K.S. Fung, G.K. Siu, S.C. Wong, L.S. Cheng, M.S. Wong, L.K. Lee, W.M. Chan, K.Y. Chau, J.S.L. Leung, A.W.H. Chu, Nosocomial Outbreak of Coronavirus Disease 2019 by Possible Airborne Transmission Leading to a Superspreading Event, Clinical Infectious Diseases. 73.6 (2021) e1356-e1364. https://doi.org/10.1093/cid/ciab313

[11] H. Helanne, E. Forsblom, K. Kainulainen, A. Järvinen, and E. Kortela, Incidence and Outcome of Hospital-Acquired Covid-19 Infections in Secondary and Tertiary Care Hospitals in the Era of Covid-19 Vaccinations, Antimicrobial Stewardship & Healthcare Epidemiology. 3.1 (2023) e216. https://doi.org/10.1017/ash.2023.489

[12] A.R. Escombe, C.C. Oeser, R.H. Gilman, M. Navincopa, E. Ticona, W. Pan, C. Martinez, J. Chacaltana, R. Rodriguez, D.A. Moore, J.S. Friedland, and C.A. Evans, Natural Ventilation for the Prevention of Airborne Contagion, PLOS Medicine. 4.2 (2007) e68. https://doi.org/10.1371/journal.pmed.0040068

[13] N. Mingotti, D. Grogono, G. dello loio, M. Curran, K. Barbour, M. Taveira, J. Rudman, C. Haworth, R. Floto, and A. Woods, The Impact of Hospital-Ward Ventilation on Airborne-Pathogen Exposure, American Journal of Respiratory and Critical Care Medicine. 203.6 (2021) 766-769. https://doi.org/10.1164/rccm.202009-3634LE

[14] H. Qian, Y. Li, W.H. Seto, P. Ching, W.H. Ching, and H.Q. Sun, Natural ventilation for reducing airborne infection in hospitals, Building and Environment. 45.3 (2010) 559-565. https://doi.org/10.1016/j.buildenv.2009.07.011

[15] H.B. Awbi, Ventilation for Good Indoor Air Quality and Energy Efficiency, Energy. 112 (2017) 277-286. https://doi.org/10.1016/j.egypro.2017.03.1098

[16] J. Atkinson (Ed.), Y. Chartier, C.L. Pessoa-Silva, P. Jensen, Y. Li, and W.H. Seto, Natural Ventilation for Infection Control in Health-Care Settings, WHO Publication/Guidelines, Canberra, 2009.

[17] S. Bhattacharyya, K. Dey, A.R. Paul, R.A. Biswas, A Novel CFD Analysis to Minimize the Spread of COVID-19 Virus in Hospital Isolation Room, Chaos, Solitons & Fractals. 139 (2020) 110294. https://doi.org/10.1016/j.chaos.2020.110294

[18] C. Méndez, J.F. San José, J.M. Villafruela, and F. Castro, Optimization of a Hospital Room by means of CFD for More Efficient Ventilation, Energy and Buildings. 40.5 (2008) 849-854. https://doi.org/10.1016/j.enbuild.2007.06.003

[19] Chau, C.H. Liu, and M.K. Leung, CFD Analysis of the Performance of a Local Exhaust Ventilation System in a Hospital Ward, Indoor and Built Environment. 15.3 (2006) 257-271. https://doi.org/10.1177/1420326X06066123

[20] C.B. Beggs, K.G. Kerr, C.J. Noakes, E.A. Hathway, and P.A. Sleigh, The Ventilation of Multiple-Bed Hospital Wards: Review and Analysis, American Journal of Infection Control. 36.4 (2008) 250-259. https://doi.org/10.1016/j.ajic.2007.07.012

[21] W.Z. Lu, A.Y. Leung, S.H. Yan, and A.T.P. So, A Preliminary Parametric Study on Performance of Sars Virus Cleaner using CFD Simulation, International Journal for Numerical Methods in Fluids. 47 (2005) 1137-1146. https://doi.org/10.1002/fld.909

[22] R.E. Stockwell, E.L. Ballard, P. O'Rourke, L.D. Knibbs, L. Morawska, and S.C. Bell, Indoor Hospital Air and the Impact of Ventilation on Bioaerosols: A Systematic Review, Journal of Hospital Infection. 103.2 (2019) 175-184. https://doi.org/10.1016/j.jhin.2019.06.016

[23] F. Mills, Indoor Air Standards in Hospitals, Business Briefing: Hospital Engineering and Facilities Management. (2004) 43–46.

[24] A.R. Escombe, E. Ticona, V. Chávez-Pérez, M. Espinoza, and D.A. Moore, Improving Natural Ventilation in Hospital Waiting and Consulting Rooms to Reduce Nosocomial Tuberculosis Transmission Risk in A Low Resource Setting, BMC Infectious Diseases. 19 (2019) 1-7.

https://doi.org/10.1186/s12879-019-3717-9

[25] ANSYS, Fluent 18 Manual, 2017.

[26] Q. Chen, Comparison of Different k-ε Models for Indoor Air Flow Computations, Numerical Heat Transfer, Part B, Fundamentals. 28.3 (1995) 353-369.
https://doi.org/10.1080/10407799508928838

[27] J. Posner, C. Buchanan, and D. Dunn-Rankin, Measurement and Prediction of Indoor Air Flow in a Model Room, Energy and Buildings. 35.5 (2003) 515-526.
https://doi.org/10.1016/S0378-7788(02)00163-9

[28] Z. Bolashikov, and A. Melikov, Methods for Cleaning and Protection of Building Occupants from Airborne Pathogens, Building and Environment. 44.7 (2009) 1378-1385.
https://doi.org/10.1016/j.buildenv.2008.09.001

[29] S. Thool, S. Sinha, Performance Evaluation of Conventional Mixing Ventilation Systems for Operating Room in the view of Infection Control by Numerical Simulation, IJBSBT. 6.4 (2014) 87-98.
http://dx.doi.org/10.14257/ijbsbt.2014.6.4.09

[30] W. Cao, B. Sun, Y. Zhao, Q. Shi, and Y. Wang, Study on the Transmission Route of Virus Aerosol Particles and Control Technology of Air Conditioning in the Enclosed Space, The European Physical Journal Plus. 136 (2021) 1-15.
https://doi.org/10.1140/epjp/s13360-021-02058-8

[31] M. Alkhalaf, A. Ilinca, and M. Hayyani, CFD Investigation of Ventilation Strategies to Remove Contaminants from a Hospital Room, Design. 7.1 (2023) 5.
https://doi.org/10.3390/designs7010005