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Experimental Study for Controlling Airborne Contaminant Exposure in Iraqi Negative Pressure Isolation Rooms

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ABSTRACT

In healthcare settings, controlling airborne contaminants is crucial for ensuring the safety of healthcare workers and patients, especially in isolation rooms designed with negative pressure systems. This paper, a novel experimental study of the distribution of airborne contamination within an Airborne Infection Isolation Room (AIIR) using tracer gas, identifies patients in Iraq to reduce the pollution and infection disease from a patient with COVID-19 or any other Respiratory patient disease by using a negative pressure room Terms of condition at three different Air Change (ACH) 6, 9 and 12 ACH. Concentrations of airborne contaminants in the breathing zone of surgical staff are measured, along with analyses of velocity, temperature, and humidity distribution in the patient's thermal plume. Negative pressure shows acceptable temperature and velocity variations according to the World Health Organization. Higher ACH and AC inlet velocities lead to decreased relative humidity and enhance heat removal efficiency, and air exchange efficiency. Contaminant removal, evaluated through the Contaminant Removal Effectiveness (CRE), exhibits superiority under high Air Conditioner AC inlet modes and increased ACH rates, recording values of 1.1 and 1.2. The study strongly recommends isolation rooms for respiratory patients in negative-pressure ventilated operating rooms to mitigate infection transmission risks to the surgical staff.

1. INTRODUCTION

The Airborne Indoor Isolation Room (AIIR) is a designated place where sick people are accepted for treatment and recuperation. In healthcare settings, the design of AIIR prioritizes the effective control of airborne contaminants, which is paramount to ensuring the safety of Health Care Workers (HCW) and patients. Isolation rooms usually designed with negative pressure systems aim to prevent the escape of potentially harmful contaminants, reducing the risk of cross-infection. Ventilation systems, play a major role in regulating air quality and minimizing the dispersion of airborne contaminants within these isolation rooms. However, there is a lack of comprehensive research comparing the efficacy of different ventilation systems in mitigating airborne contaminant exposure. This study aims to bridge this knowledge gap by conducting an experimental analysis of ventilation systems' performance in Iraqi negative pressure isolation rooms. Previous studies have investigated various aspects related to airborne contaminant exposure and ventilation systems. Melikov et al. [1] demonstrated the accurate measurement of temperature, humidity, and pollution concentration in inhaled air using thermal manikins. Liu et al. [2] developed an air curtain ventilation system that effectively minimized the concentration of coughed particles in protected zones. Proper ventilation strategies in patient rooms were highlighted by Mousavi et al. [3] to contain and remove bioaerosols. Cao et al. [4] demonstrated the potential of protected zone ventilation in reducing the transmission of exhaled air between individuals. Offermann et al. [5] emphasized the significance of proper ventilation configurations and keeping doors closed to minimize particle transfer in hospital settings. Berlanga et al. [6] reported positive results in terms of ventilation, pollutant control, and overall comfort indices when using displacement ventilation in airborne virus isolation rooms. Various other studies have investigated ventilation systems' efficacy in mitigating the transmission of infectious diseases, optimizing air inlet/outlet locations, and the interplay between thermal plumes and laminar airflow. Currently, there is a lot of scientific research on COVID-19, particularly for public health interventions and engineering methods for enhancing Indoor Air Quality (IAQ). The isolation ward mostly prevented contaminants from flowing out by regulating the pressure differential between the wards. Table 1 shows a summary of the previous studies with different specific conditions. The research gap in the available literature regarding the lack of comprehensive studies specifically addressing this topic in the context of Iraqi healthcare facilities. While there may be existing research on airborne contaminant control in an office or classroom. Also, there is a dearth of literature specifically focusing on these aspects within the Iraqi healthcare setting which considers the unique contextual factors, such as local climate, building design, healthcare practices, and potential variations in room designs and ventilation systems specific to Iraq. The current study can contribute to the existing literature by providing insights and recommendations that are tailored to the Iraqi healthcare context. The findings of such a study can inform the development of guidelines and protocols for controlling airborne contaminant exposure in negative pressure isolation rooms in Iraq, thereby enhancing the safety of patients and healthcare workers and improving infection control measures in the country. In the present study, several experimental tests investigated various air conditioning system configurations and their experimental implications for achieving the desired negative pressure in isolation rooms. By analyzing the data and considering the interplay of key parameters, this study aims to provide insights into optimizing the design and operation of air conditioning systems and air change to enhance isolation effectiveness and ventilation in negative pressure rooms. This work provides the findings of experimental research conducted at the University of Technology to investigate the behavior and features of a real space. The research aims to acquire insights into many characteristics of space, such as its airflow mode, air change, ventilation system, temperature distribution, and air quality.

Table 1. A summary of previous surveys

Space of Study	Case Study	Results
Bedroom.	Air purifying respirators with or without HEPA filtration.	Positive effects of filtration require substantial exposure contrasts, especially in the bedroom, and possibly not confounding by drug intake or existing disease [7].
Room.	Three ventilation MV, One and two-slot POV	The decreased air velocity distribution may increase the patient's exposure to various indoor airborne pollutants during orthopedic surgery [8].
Office room.	Comparison between AC types.	The 4-way cassette is better than MV AC [9].
Operating room.	4 different cases were examined with a real person and a thermal Manikin.	The decreased air velocity distribution may increase the patient's exposure to various indoor airborne pollutants during orthopedic surgery [10].
Hospital.	Three engineering strategies.	The “low-level extraction” technique of ventilation systems effectively removes pollutants [11].
A ventilated room.	Three different AC gate angles.	Increasing the AC inlet gate angle leads to flow distribution in the room with weak vortices [12].
Hospitals.	Various ventilation strategies were designed.	Pollutant removal was greatly influenced by the position of the exit; however, increased ventilation alone does not necessarily enhance air dispersion [13].
Isolated room	Three ceiling AC angles 0°, 15°, and 30°	Ceiling 4-way cassette AC enhances airborne contaminants elimination [14].

2. METHODOLOGY

The study involved experimental work, where measurements related to airflow rate, air quality, and thermal comfort will be conducted. In this research, controlled experiments will be conducted in a simulated negative pressure isolation room. Various ventilation systems, including mechanical, natural, and hybrid systems, will be tested. Airborne contaminant concentrations will be measured at different locations in the room using appropriate sampling methods and equipment. Negative pressure was maintained by regulation outlet extract. To mimic real-world conditions, tracer gases or simulated contaminants will be released during the experiments. Throughout the process, variables such as pressure differentials, airflow patterns, and air exchange rates will be monitored and controlled. The collected data will undergo statistical analysis to evaluate the effectiveness of different ventilation systems and identify any significant differences in airborne contaminant exposure.

2.1 Test room and experimental setup

In the specially designed Airborne Indoor Isolation Room (AIIR), experiments investigated indoor air quality, ventilation, and airborne contamination. The AIIR is constructed to effectively separate individuals carrying contagious diseases and prevent the spread of infectious airborne particles. To maintain a negative air pressure differential compared to surrounding areas and achieve high air changes (ACH), the AIIR is built with precise dimensions and a specialized ventilation system. The control of indoor carbon dioxide (CO_2) levels is crucial for ventilation and indoor air quality (IAQ) in the isolation room, as low IAQ can lead to immediate and long-term health issues. The AIIR is equipped with lighting and a thermal manikin that generates a combined heat load to simulate human heat emissions. The thermal space characteristics of the room are defined according to ANSI/ASHRAE Standard 55-2010, and Table 2 provides detailed descriptions.

The ventilation used not only dilutes contaminants but also transports gaseous and particulate matter, provides freshness, and assesses the effectiveness of the HVAC system. The 4-way cassette air conditioning system used in the AIIR.

Table 2. Room configuration parameter of desired conditions (all dimensions in meters)

Item	Location (m)					
	Start			End		
	X	Y	Z	X	Y	Z
Room	0	0	0	3	2.5	2.3
Patient	1.4	2.4	0.65	1.6	0.65	0.92
Doctor	1.9	1.15	0	2.12	1.72	1.75
AC	1.25	1.5	2.3	1.75	2	2.3
Inlet	1.35	2.5	1.9	1.65	2.5	2.2
Exhaust grille	0.2	0	0.1	0.5	0	0.4
Light 1	1.05	1	2.3	1.15	1.5	2.3
Light 2	1.85	1	2.3	1.95	1.5	2.3
Door	2.82	0	0	2.9	0	1.8

2.2 Thermal mannikins

Two thermal manikins were utilized in the study conducted inside the AIIR at the University of Technology-Baghdad-Iraq as shown in Figure 1. These manikins represented a patient lying on a hospital bed and a healthcare worker standing close to the patient. The manikins were carefully placed within the AIIR to simulate realistic scenarios as presented in Figure 2. The 1.85-meter-tall [15] healthcare worker manikin was created to resemble a man of average size. It was wearing a doctor's uniform. In contrast, the patient manikin was dressed in light surgical and had the proportions of an average-sized man standing 1.8 meters tall. The manikins' geometric features were painstakingly designed to mimic real people closely. Both manikins' breathing mechanisms were turned on to guarantee more precise measurements

Figure 1. Experimental equipment and measuring plane

2.3 Measurement procedure and instrument

The experimental setup in the Airborne Infection Isolation Room (AIIR) laboratory involved the continuous release of CO_2 tracer gas through a plastic tube (φ33 mm). A gas rotameter connected to a gas cylinder regulated the CO_2 flow rate. The CO_2 system included Arduino-controlled valves to replicate inhalation and exhalation states and a two-way pump simulated breathing movements. Before each experiment, the AIIR lab underwent a 2-hour pre-ventilation period, and tracer gas release began once the indoor temperature stabilized at around (24-26)°C. Measurements were taken at 33 nodes, with a sequential time interval of 2 minutes at each location, totaling 99 sensors. The sampling duration ranged from 120 to 180 minutes. Each node in the AIIR had three sensors for temperature and humidity, velocity, and CO_2 concentration. To ensure accuracy, each experimental case was repeated twice, and a clean-up procedure was performed between cases to maintain CO_2 concentration below 0.5 ppm. The experimental measurement focused on three planes representing different internal conditions. The analysis aimed to evaluate mean values of horizontal distribution at nine nodes in each plane, including outlets and locations near the door. The nodes were strategically placed at lower, breathing, and higher planes to ensure comprehensive coverage. The vertical plane was also investigated for any significant effects. Table 3 provides details of the planes used for assessment, while Table 4 illustrates the specific locations of each node.

Figure 2. Thermal breathing manikins were used in this study to simulate the patient

2.4 Investigated cases

Nine experimental cases were conducted using tracer gas to examine the effects under varying conditions involving an air conditioner and a ventilation system. Different modes of the air conditioner, including high, moderate, and low settings, were utilized under differential negative pressure. The pressure difference within the AIIR (Airborne Infection Isolation Room) was modified by controlling the rate of air extraction. The specific measurement conditions for each case are detailed in Table 5.

2.5 Contaminant removal effectiveness

Contaminant Removal Effectiveness (CRE) refers to the efficiency or effectiveness of a system or method in removing contaminants from a given environment. It quantifies the ability of a ventilation system, air purification device, or other engineering control measures to eliminate or reduce the concentration of contaminants in a specific space [16-24]. The difference between the two concentrations is used to determine the effectiveness of the system in removing the contaminants as shown in the equation below [2, 19].

Table 3. Characteristics of the measurement system

Sensor -Model	Function	Range	Resolution	Accuracy
Mg-811 GAS	CO_2	350 to 10000 ppm	10 ppm	± 1 ppm
DHT11	Temperature	0 ~50℃	1℃	±1℃
	Humidity	0-100% RH	0.1% RH	± 4% RH
Wind sensor Rev. C	Air velocity	0.2 to 20 m/s	0.01 m/s	± 0.025 m/s
GAS CCS811 CO_2 Gas sensor	CO_2	400 to 9000 ppm	10 ppm	± 1 ppm

Table 4. Coordinated sections in the test room (CO_2, velocity, temperature, and relative humidity)

Position	Plane name	X-axis	Y-axis	Z-axis
1	Plane 1	3 m	2.3 m	0.2 m
2	Plane 2	3 m	2.3 m	1.25 m
3	Plane 3	3 m	2.3 m	2.3 m

Table 5. Measurement conditions

6 ACH		9ACH		12 ACH	
Case Number	AC Mode	Case Number	AC Mode	Case Number	AC Mode
Case1	High	Case 4	High	Case 7	High
Case2	Medium	Case 5	Medium	Case 8	Medium
Case3	Low	Case 6	Low	Case 9	Low

$$\varepsilon = \frac{C_e - C_s}{C_b - C_s} \quad (1)$$

The letters C_e, C_s, and C_b represent, respectively, the contaminant concentrations at the exhaust, supply, and average contaminant concentrations in the respiratory zone (1.2–1.7 m above the floor).

2.6 Heat removal effectiveness

Heat removal efficiency refers to the effectiveness with which heat is extracted or removed from a system or space. It is a measure of how well a cooling can reduce the temperature or remove heat from a given area [20-22]. A higher value of ε indicates a more effective heat removal process, while a lower value indicates less effective heat removal [23, 24]. Heat removal efficiency in AIIR as stated by:

$$\varepsilon_t = \frac{T_{out} - T_{mean}}{T_{in} - T_{mean}} \quad (2)$$

where, ε: Heat removal effectiveness (dimensionless), T_{out}: Outlet temperature of the heat transfer process (in °C or °F), T_{in}: Inlet temperature of the heat transfer process (in °C or °F), and T_{mean}: Mean temperature of the heat transfer process, which is calculated as $(T_{out} + T_{in}) / 2$ (in °C or °F).

2.7 Air Diffusion Performance Index (ADPI)

The Air Diffusion Performance Index (ADPI) is a metric used to evaluate the performance of air distribution systems within occupied spaces. It measures the proportion of measurements conducted within the space that falls within the range of effective draught temperatures, typically ranging from -1.5°C to +10°C. Higher ADPI values indicate better performance, with an ADPI of 80% or above considered desirable in most cases. ADPI is used and applicable for cooling mode only [25, 26]. ADPI can evaluated from:

$$\theta = (t_x - t_c) - 8(V_x - 0.15) \quad (3)$$

$$ADPI = (N_\theta\ \theta / N) \times 100\% \quad (4)$$

3. RESULTS AND DISCUSSION

3.1 Measurement of temperature distribution

In Figure 3, the measurements were conducted under a negative pressure differential. The results indicate that at a low AC mass flow rate, the temperature distribution has higher values compared to the medium flow rate. The medium flow rate registers slightly higher temperatures than the high flow rate.

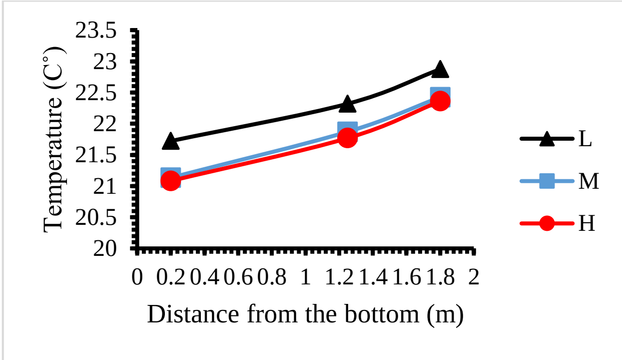

Figure 3. Air temperature of horizontal planes in the AIIR at 6 ACH and three different AC modes

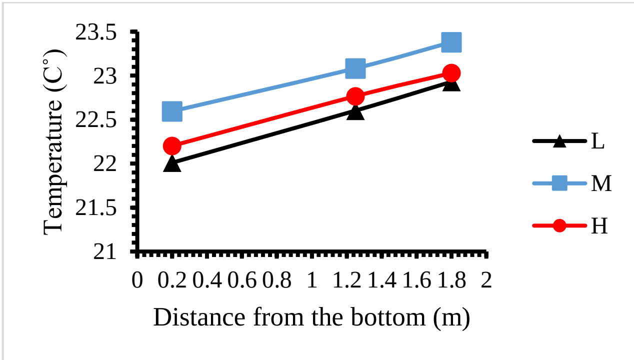

Figure 4. Air temperature of horizontal planes in the AIIR at 9 ACH and three different AC modes

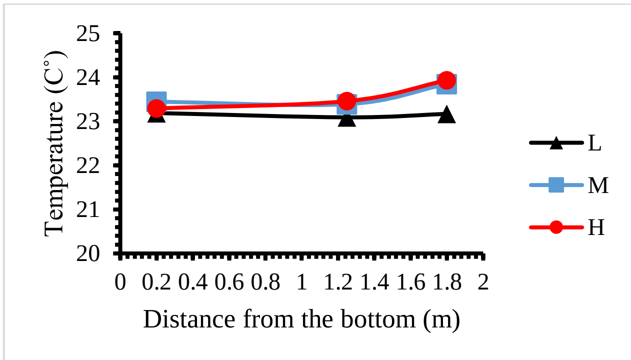

Figure 5. Air temperature of horizontal planes in the AIIR at 12 ACH and three different AC modes

In Figure 4, the findings reveal that the medium AC mass flow rate exhibits higher temperature values compared to both the high and low AC mass flow rates. This temperature disparity can be attributed to the balanced and uniform distribution of air facilitated by the medium AC mass flow rate, promoting effective heat dispersion and optimized heat transfer processes within the room.

Figure 5 indicated that the results indicate that the temperature associated with the higher AC inlet mass flow rate is higher compared to the moderate and low mass flow rates. The moderate mass flow rate exhibits higher temperatures than the low mass flow rate. At 12 ACH, the temperature gradients across the vertical distance from the ground are less pronounced, indicating a more uniform temperature distribution within the room.

3.2 Measurement of velocity distribution

Figure 6 indicates that Increasing the AC inlet air flow rate results in higher velocities, and decreasing it leads to lower velocities causing the stratification of horizontal three planes.

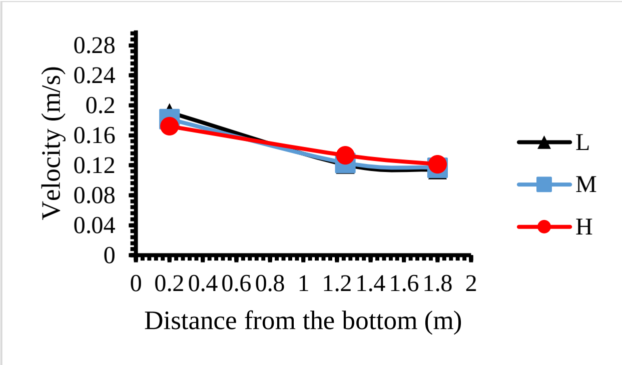

Figure 6. Air velocity of horizontal planes in the AIIR at 6 ACH and three different AC modes

Figure 7 illustrates that Air velocity is highest at the bottom plane, followed by a decrease at the breathing plane and an increase at the top plane. Increasing the AC inlet air flow rate leads to higher velocities, and decreasing it results in lower velocities.

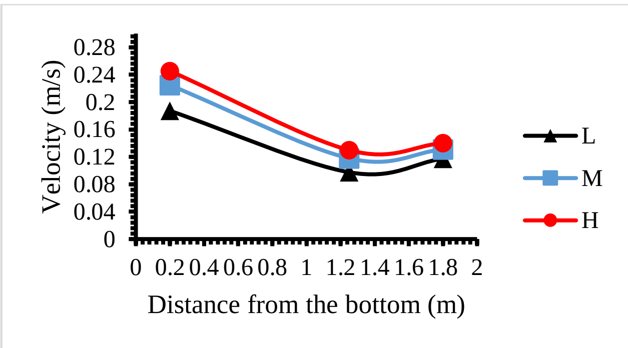

Figure 7. Air velocity of horizontal planes in the AIIR at 9 ACH and three different AC modes

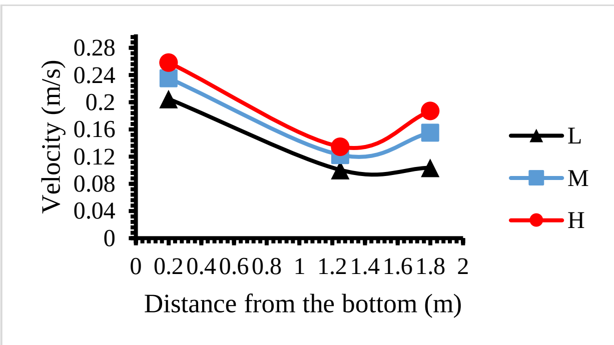

Figure 8. Air velocity of horizontal planes in the AIIR at 12 ACH and three different AC modes

Figure 8 shows Air velocity is highest at the bottom plane, followed by a decrease at the breathing plane and an increase at the top plane. Differences in air velocity among low, moderate, and high AC inlet air conditions are consistent. Increasing the AC inlet air flow rate leads to higher velocities, and decreasing it results in lower velocities. This observation explains why a difference in air velocity in the previous studies [9, 27-29] compared to the numerical and experimental results in the current study.

3.3 Measurement of CO_2 concentration distribution

In Figure 9 at an ACH of 6 and a pressure differential of -10 Pa, similar trends are observed with gradually increasing CO_2 concentrations over time. The presence of a ceiling air conditioning system contributes to the mixing of CO_2 and its distribution throughout the room. Figure 10, case 4, at an ACH of 9, similar patterns are observed with high CO_2 concentrations at low AC mass flow rates and lower concentrations at moderate and high AC mass flow rates. Figure 11 shows that the higher negative pressure differential helps to prevent contaminated air from escaping the room, but it does not significantly impact CO_2 concentrations. The aforementioned implications make it abundantly evident that a careful comprehension of the point of view is beneficial, particularly when it comes to exposure to indoor pollutants. Increases in air change rate have been linked to higher levels of exposure to expiratory released aerosols, according to the findings of multiple recent studies [30-32]. These studies unequivocally demonstrate that the primary determinants of exposure to expiratory aerosols are the intricate flow interactions between airflow patterns produced by the air delivery systems. While, in the current ventilation system, the pollutants become more in the lower part and have no other outlet but to exit through the ventilation outlet which helps reduce airborne contaminant exposure.

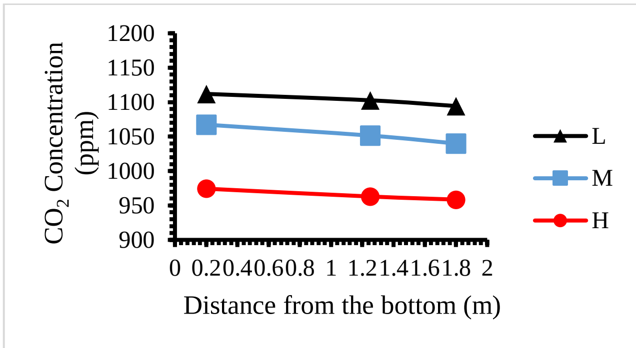

Figure 9. CO_2 concentration of horizontal planes in the AIIR at 6 ACH and three different AC modes

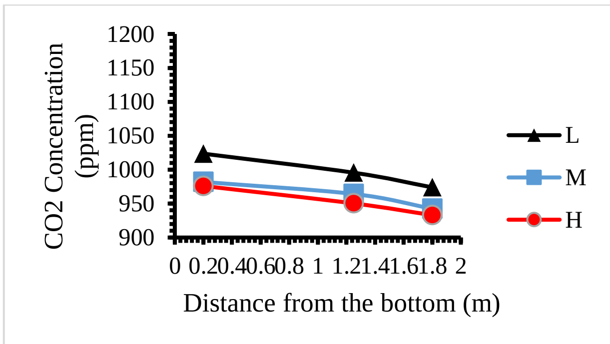

Figure 10. CO_2 concentration of horizontal planes in the AIIR at 9 ACH and three different AC modes

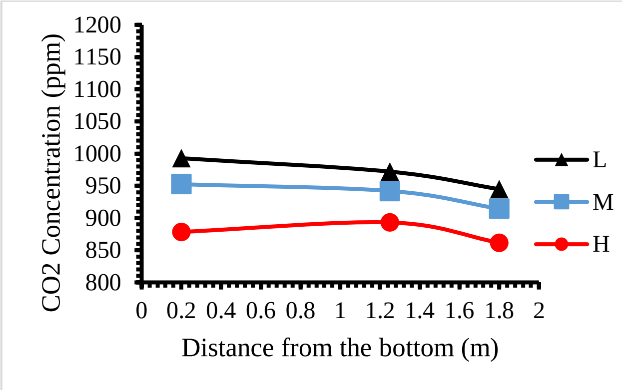

Figure 11. CO_2 concentration of horizontal planes in the AIIR at 12 ACH and three different AC modes

3.4 Contaminant Removal Effectiveness (CRE)

The Contaminant Removal Effectiveness (CRE) serves as a key metric in evaluating the efficiency of contaminant removal within Airborne Infection Isolation Rooms (AIIRs) under various conditions. Across the different cases analyzed, the trends in Contaminant Removal Efficiency (CRE) over time and under different Air Change (AC) inlet modes provide valuable insights into the performance of these environments.

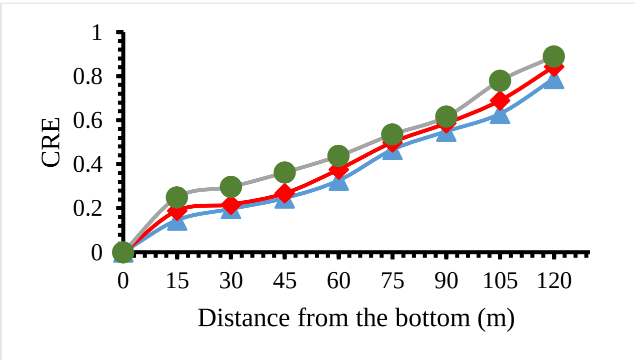

Figure 12. CRE with time in the AIIR at 6 ACH and three different AC modes

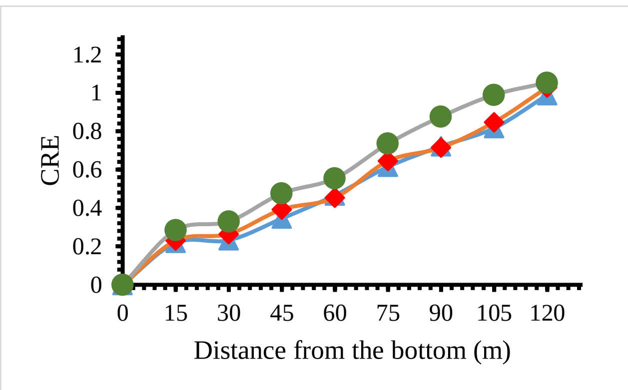

Figure 13. CRE with time in the AIIR at 9 ACH and three different AC modes

In Figure 12, the CO_2 concentration in an Airborne Infection Isolation Room (AIIR) highlights a continuous improvement in contaminant removal efficiency with time, with final CRE values reaching 0.82, 0.88, and 0.95 under low, moderate, and high AC inlet mode conditions. Subsequent cases demonstrate similar upward trajectories in CRE, indicating enhanced contaminant control. The values in Figure 12 although lower, still reflect a positive trend over time. Figure 13 shows that demonstrates superior CRE values of 1.03, 1.1, and 1.2 under low, moderate, and high AC inlet modes, surpassing those recorded at lower Air Change Rates (ACH) of 6 and 9. Finally, Figure 14 underscores the significance of higher ACH rates, revealing a consistent increase in CRE values to 1.01, 1.05, and 1.15 under low, moderate, and high AC inlet modes. Notably, these values surpass those recorded under ACH rates of 6 and 9, emphasizing the critical role of elevated air change rates in achieving superior contaminant control within AIIRs) is recorded to have high values. However, this assumption also improved with displacement ventilation in previous studies [6].

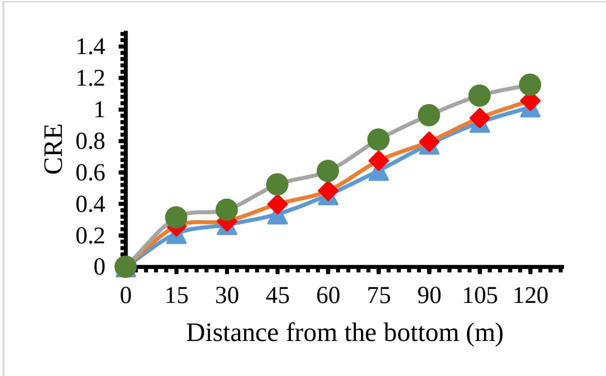

Figure 14. CRE with time planes in the AIIR at 12 ACH and three different AC modes

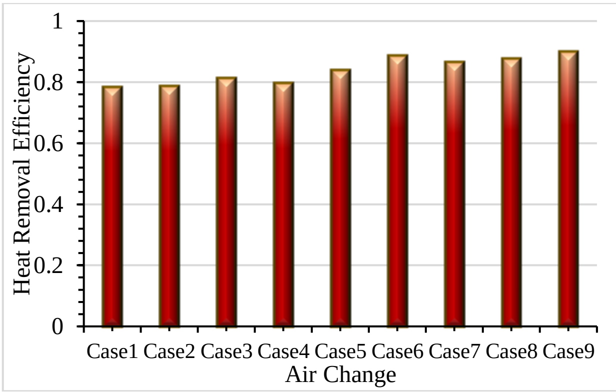

Figure 15. Heat removal efficiency with 6, 9 and 12 ACH

3.5 Heat removal efficiency (HRE) and air change efficiency

Heat removal efficiency is a measure of how effectively a system or environment removes heat to maintain a desired temperature or thermal equilibrium. Figure 15 shows that the efficiency of heat removal within the isolation room demonstrates an upward trend as the Air Change Rates (ACH) increase from 6 to 9 and 12. Conversely, when the isolation room operates at 6, 9, and 12 ACH, the heat removal efficiency experiences an increase from 0.78 to 0.89. This indicates that, under negative pressure conditions, the efficiency of heat removal is enhanced as the ACH rates escalate. From Figure 16 it can be observed that as the air change rate (ACH) increases, the air change efficiency also tends to increase in case 6. This indicates that higher air change rates result in a more effective removal of contaminants from the space.

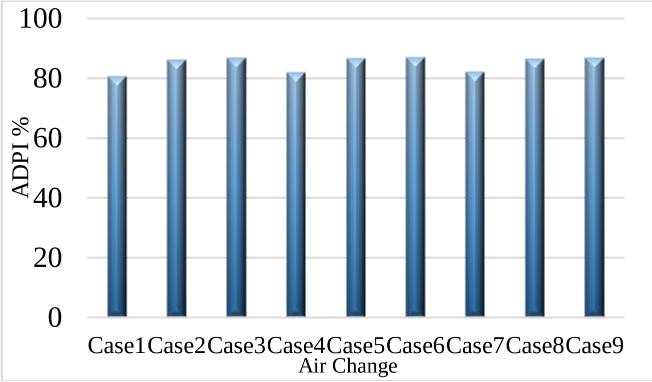

Figure 16. ADPI with 6, 9 and 12 ACH at 12 ACH

3.6 Air Diffusion Performance Index (ADPI)

Figure 16 observes that the ADPI values range from around 79% to 86%, indicating that a majority of the occupied locations meet the thermal comfort criteria. Furthermore, the ACH values, which vary from 6 to 12, indicate a respectable amount of air changes per hour, which supports adequate ventilation and air quality in the area. Based on the ADPI values, these results imply that the studied spaces generally have good thermal comfort and air distribution performance. Reasonable ventilation rates are indicated by the ACH values, and these help to preserve good air quality.

4. LIMITATIONS OF THIS STUDY

The present paper discusses several practical that provide the guidelines and recommendations of ASHRAE and the World Health Organization. However, some practical have not been evaluated such as the potential congestion of corridors also opening doors during entry and exit. When designing isolation room to combat severe infectious diseases, it is commonly assumed the number of persons is less, typically one or two individuals, as supported by previous studies [33-35].

This assumption is reasonable in the context of public buildings, where individuals with symptomatic severe infectious diseases are usually quarantined and not permitted to enter such buildings.

5. CONCLUSION

The current investigation studied the airborne contamination distribution originating from respiratory patients in an Airborne Infection Isolation Room (AIIR) experimentally employing tracer gas. The contamination sources were identified as the patient. Concentrations of airborne contaminants in the breathing zone of surgical staff within the AIIR were measured in Iraqi conditions. The study's conclusions are as follows:

- The temperature distribution exhibits a stratified pattern at low Air Change Rates (ACH), with an observed uniform decrease in temperature when increasing Air Change (AC) inlet mass flow rates.
- Higher ACH and AC inlet velocities lead to decreased relative humidity in AIIRs, with increased negative pressure enhancing air exchange and reducing moisture levels.
- Air velocity distributions increase with rising ACH values and AC velocity mode, contributing to the rapid dilution and removal of contaminants.
- Contaminant removal efficiency is influenced by ACH and AC velocity modes, with superior (CRI) values observed under high AC inlet modes and increased ACH rates in the third case which revealed 1.2. Higher ACH rates, combined with appropriate AC velocities and negative pressure settings, contribute to superior contaminant removal efficiency within AIIRs.
- Air Diffusion Performance Index (ADPI) values and ACH rates play a crucial role in ensuring the health and well-being of occupants by effectively managing air quality and preventing contaminant dissemination under negative pressure conditions revealing 89% at 12 ACH.
- Increasing ACH significantly enhances heat removal efficiency. The upward trend in heat removal efficiency as ACH rates increase from 6 to 9 and 12 indicates the effectiveness of the system reaches 0.86.
- It is strongly recommended that patients with respiratory diseases undergo surgical procedures in negative-pressure ventilated operating rooms. This precautionary measure aims to mitigate the risk of infection transmission to surgical staff by establishing a differential pressure environment, containing the dissemination of airborne contaminants, including potentially infectious particles.
- Further work can Investigate renewable energy sources that can help reduce airborne contaminant exposure by using clean energy to reduce fossil fuels and contribute to emissions elimination.
- It is commonly recommended to avoid using recirculation for outlet air, maintain the room at positive pressure, and open entry practices, especially for patients with respiratory disease.

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REFERENCE

[1] Melikov, A., Kaczmarczyk, J. (2007). Measurement and prediction of indoor air quality using a breathing thermal manikin. Indoor Air, 17(1): 50-59. https://doi.org/10.1111/j.1600-0668.2006.00451.x

[2] Liu, Z.J., Wang, Y., Xiao, X., Zhang, Z., Liu, H., He, J., Li, S., Liang, Z. (2022). A novel design strategy to interrupt the diffusion of exhaled aerosols: An integrated experimental-numerical investigation. SSRN. https://doi.org/10.2139/ssrn.4166072

[3] Mousavi, E.S., Grosskopf, K.R. (2015). Ventilation rates and airflow pathways in patient rooms: A case study of bioaerosol containment and removal. Annals of Occupational Hygiene, 59(9): 1190-1199. https://doi.org/10.1093/annhyg/mev048

[4] Cao, G., Siren, K., Nielsen, P.V, Novoselac, A. (2015).

Protected zone ventilation for reducing Protected zone ventilation for reducing personal exposure to indoor pollutants. Indoor Air, 25(3): 307-319. https://doi.org/10.1111/ina.12142
[5] Offermann, F.J., Eagan, A., Offermann, A.C., Subhash, S.S., Miller, S.L., Radonovich, L.J. (2016). Potential airborne pathogen transmission in a hospital with and without surge control ventilation system modifications. Building and Environment, 106: 175-180. https://doi.org/10.1016/j.buildenv.2016.06.029
[6] Berlanga, F.A., Adana, M.RD., Olmedo, I., Villafruela, J.M., José, J.F.S., Castro, J. (2018). Experimental evaluation of thermal comfort, ventilation performance indices and exposure to airborne contaminant in an airborne infection isolation room equipped with a displacement air distribution system. Energy and Buildings, 158: 209-221. https://doi.org/10.1016/j.enbuild.2017.09.100
[7] Karottki, D.G., Spilak, M., Frederiksen, M., Gunnarsen, L., Brauner, E.V., Kolarik, B., Andersen, Z.J., Sigsgaard, T., Barregard, L., Strandberg, B., Sallsten, G., Møller, P., Loft, S. (2013). An indoor air filtration study in homes of elderly: Cardiovascular and respiratory effects of exposure to particulate matter. Environmental Health, 12: 116. https://doi.org/10.1186/1476-069X-12-116
[8] Liu, S., Cao, G., Boor, B.E., Novoselac, A. (2014). A protected occupied zone ventilation system to prevent the transmission of coughed particles. UC Berkeley Previously Published Works. https://escholarship.org/uc/item/85j9m402.
[9] Bamodu, O., Xia, L., Tang, L. (2017). A numerical simulation of air distribution in an office room ventilated by 4-way cassette air-conditioner. Energy Procedia, 105: 2506-2511. https://doi.org/10.1016/j.egypro.2017.03.722
[10] Cao, G., Storås, M.C.A., Aganovic, A., Stenstad, L.I., Skogås, J.G. (2018). Do surgeons and surgical facilities disturb the clean air distribution close to a surgical patient in an orthopedic operating room with laminar airflow? American Journal of Infection Control, 46(10): 1115-1122. https://doi.org/10.1016/j.ajic.2018.03.019
[11] Cho, J. (2019). Investigation on the contaminant distribution with improved ventilation system in hospital isolation rooms: Effect of supply and exhaust air diffuser configurations. Applied Thermal Engineering, 148: 208-218. https://doi.org/10.1016/j.applthermaleng.2018.11.023
[12] Aljabair, S., Alesbe, I., Alkhalaf, A. (2023). CFD modeling of influenza virus diffusion during coughing and breathing in a ventilated room. Journal of Thermal Engineering, 9(1): 127-137. https://doi.org/10.18186/thermal.1243491
[13] Alkhalaf, M., Ilinca, A., Hayyani, M.Y. (2023). CFD investigation of ventilation strategies to remove contaminants from a hospital room. Designs, 7(1): 5. https://doi.org/10.3390/designs7010005
[14] Barrak, E., Hussain, H., Habeeb, L. (2024). Numerical investigation of air conditioning system configurations for achieving desired negative pressure in isolation rooms. Engineering and Technology Journal, 42(1): 232-248. https://doi.org/10.30684/etj.2023.142987.1553
[15] Aganovic, A., Steffensen, M., Cao, G. (2019). CFD study of the air distribution and occupant draught sensation in a patient ward equipped with protected zone ventilation. Building and Environment, 162: 106279. https://doi.org/10.1016/j.buildenv.2019.106279
[16] Lu, Y.L., Oladokun, M., Lin, Z. (2020). Reducing the exposure risk in hospital wards by applying stratum ventilation system. Building and Environment, 183: 107204. https://doi.org/10.1016/j.buildenv.2020.107204
[17] Berlanga, F.A., Adana, M.R.D., Olmedo, I., Villafruela, J.M., José, J.F.S., Castro, F. (2018). Experimental evaluation of thermal comfort, ventilation performance indices and exposure to airborne contaminant in an airborne infection isolation room equipped with a displacement air distribution system. Energy and Buildings, 158: 209-221. https://doi.org/10.1016/j.enbuild.2017.09.100
[18] Cheng, Z., Aganovic, A., Cao, G.Y., Bu, Z.M. (2021). Experimental and simulated evaluations of airborne contaminant exposure in a room with a modified localized laminar airflow system. Environmental Science and Pollution Research, 28: 30642-30663. https://doi.org/10.1007/s11356-021-12685-4
[19] Olmedo, I., Nielsen, P.V., Adana, M.R.D., Jensen, R.L., Grzelecki, P. (2012). Distribution of exhaled contaminants and personal exposure in a room using three different air distribution strategies. Indoor Air, 22(1): 64-76. https://doi.org/10.1111/j.1600-0668.2011.00736.x
[20] Saheb, H.A., Mahdi, A.A., Al-amir, Q.R. (2021). A comparative study of performance between two combined ventilation systems and their effect on indoor air quality and thermal comfort inside office rooms. IOP Conference Series: Materials Science and Engineering, 1095: 012001. https://doi.org/10.1088/1757-899x/1095/1/012001
[21] Jasim, S.S., Mahdi, A.A. (2023). Assessment of turbulence models by using a mixing ventilation system with partitioned office room to predict temp distribution and thermal comfort. AIP Conference Proceedings, 2830(1): 070019. https://doi.org/10.1063/5.0157404
[22] Nayyef D.R., Mahdi, A.A. (2023). Numerical comparison of thermal comfort and air age between two combined ventilation systems with chilled ceiling considering occupant density. International Journal of Heat and Technology, 41(1): 213-223. https://doi.org/10.18280/ijht.410123
[23] Sabr, A.H., Aljibory M.W., Mahdi, A.A. (2024). Experimental and numerical study for Assessment indoor air quality by Adopting Mixing Ventilation with different occupants' density in Iraq hot climates. Journal of Thermal Engineering, 2(10): 430-446 https://doi.org/10.18186/thermal.1456666
[24] Jassim, S.S., Mahdi, A.A. (2023). An investigation of a nonthermally insulated mixing ventilated office room for partitioning in hot and dry climate by simulation approach. Heat Transfer, 52(3): 2207-2230. https://doi.org/10.1002/htj.22781
[25] Nayyef, D.R., Mahdi, A.A. (2023). Experimental study for comparison of thermal comfort and air age between two combined ventilation systems with chilled ceiling considering occupant density. Heat Transfer, 52(5): 3557-3581. https://doi.org/10.1002/htj.22840
[26] Yakoop, A.K., Yassen, W., Hwalah, S.M., Mahdi, A.A., Al-Amirb, Q.R. (2022). Experimental investigation of adding a personal ventilation system as combined with hybrid ventilation system during isolated office rooms.

International Journal of Heat and Technology, 40(5): 1150-1156. https://doi.org/10.18280/ijht.400505
[27] Voelker, C., Alsaad, H. (2018). Simulating the human body's microclimate using automatic coupling of CFD and an advanced thermoregulation model. Indoor Air, 28(3): 415-425. https://doi.org/10.1111/ina.12451
[28] Licina, D., Pantelic, J., Melikov, A., Sekhar, C., Tham, K.W. (2014). Experimental investigation of the human convective boundary layer in a quiescent indoor environment. Building and Environment, 75: 79-91. https://doi.org/10.1016/j.buildenv.2014.01.016
[29] Mareed, W., Hussen, H. (2020). Numerical and experimental modeling of indoor air quality inside a conditioned space with mechanical ventilation and DX-air conditioner. Engineering and Technology Journal, 38(9A): 1257-1275. https://doi.org/10.30684/etj.v38i9a.875
[30] Pantelic, J., Tham, K.W. (2013). Adequacy of air change rate as the sole indicator of an air distribution system's effectiveness to mitigate airborne infectious disease transmission caused by a cough release in the room with overhead mixing ventilation: A case study. HVAC and R Research, 19(8): 947-961. https://doi.org/10.1080/10789669.2013.842447
[31] Bolashikov, Z.D., Melikov, A.K., Kierat, W., Popioek, Z., Brand, M. (2012). Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation. HVAC and R Research, 18(4): 602-615. https://doi.org/10.1080/10789669.2012.682692
[32] Melikov, A.K., Bolashikov, Z.D., Kostadinov, K., Kierat, W., Popiolek, Z. (2012). Exposure of health care workers and occupants to coughed air in a hospital room with displacement air distribution: Impact of ventilation rate and distance from coughing patient. In 10th International Conference on Healthy Buildings, Brisbane, Australia.
[33] Melikov, A.K., Ai, Z.T., Markov, D.G. (2020). Intermittent occupancy combined with ventilation: An efficient strategy for the reduction of airborne transmission indoors. Science of the Total Environment, 744: 140908. https://doi.org/10.1016/j.scitotenv.2020.140908
[34] Dai, H., Zhao, B. (2020). Association of the infection probability of COVID-19 with ventilation rates in confined spaces. Building Simulation, 13: 1321-1327. https://doi.org/10.1007/s12273-020-0703-5
[35] Zhang, J. (2020). Integrating IAQ control strategies to reduce the risk of asymptomatic SARS CoV-2 infections in classrooms and open plan offices. Science and Technology for the Built Environment, 26(8): 1013-1018. https://doi.org/10.1080/23744731.2020.1794499

NOMENCLATURE

ε	Contaminant removal effectiveness.
εt	Heat removal effectiveness (dimensionless).
Ce	Contaminant concentration at the exhaust.
Cs	Concentration of contaminants at the source.
Cb	Contaminant concentration at the typical contaminant.
Cex	Contaminant concentration in the exhaled flow.
Tin	Inlet temperature (℃ or ℉).
Tmean	Mean temperature (℃ or ℉).
Tout	Outlet temperature (℃ or ℉).
Tx	Supply air temperature (℃).
Tc	Temperature (℃).
N	Total number of air terminal devices.
V	Velocity of supply air.

Abbreviations

AC	Air Conditioner.
ADPI	Air Diffusion Performance Index
AIIR	Airborne Indoor Isolation Room.
ACH	Air Change.
CRE	Contaminant removal effectiveness.
HRE	Heat Removal Effectiveness.
IAQ	Indoor Air Quality.