Efficient Ventilation Configurations for an Isolation Ward in View of Reducing the Potential Contamination of Its Occupants

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ABSTRACT

The rise of respiratory infections, such as the SARS epidemic in 2003, and the H1N1 influenza epidemic in 2011, highlighted the importance of efficient ventilation in healthcare facilities. The novel SARS -Cov-2 disease has sparked many concerns over the ventilation performance of multi-bed isolation wards and their ability to suppress airborne infectious contamination. The study is primarily based on suggesting ventilation improvements for a locally acquired multi-bed intensive care isolation unit. The study via ANSYS -fluent incorporates a k-ε turbulent model that is used to analyze exhaled CO_2 particle tracks of 4 human models. Three ventilation strategies, namely, Displacement, Stratum, and Curtain -Air-jet are initially considered and evaluated based on two indoor air quality indices (IAQs), namely, air change efficiency and contaminant removal effectiveness. Stratum ventilation comfortably exhibits unidirectional flow characteristics with an air change efficiency of 0.946, which was obtained through ANSYS -CFX while each suggested configuration is capable of achieving a contaminant removal effectiveness value greater than 1 which depicts that the contamination source is not in a perfect mixing zone. Results provided inconclusive evidence to draw correlations between the two IAQ indices and thus it is confirmed that these indices solely depend on the type of ventilation strategy. Contaminant concentration on health care worker breathing plane and exhaled particle tracking for 4 minutes in each analyzed configuration revealed that both Stratum and Curtain air-jet models improve the escaped particle efficiency by 25% and 29% respectively compared to the base model. These models are further compared against reference values specified by guidelines to evaluate their suitability for real-world operation.

KEYWORDS: *Ventilation, efficiency, ANSYS, isolation, airborne particles, Displacement, Stratum, Curtain -Air-jet*

1. INTRODUCTION

Airborne infectious diseases such as severe acute respiratory syndrome (SARS) in 2003, H1N1 influenza in 2009, droplet infectious diseases such as Ebola (2013-2014) in Africa, and the novel SARS -CoV- 2 diseases originating from Wuhan, China has sparked major concerns over the disease control actions implemented in recent years even with the development of technology. Implementation of proper ventilation strategies that mitigates pathogen transmission via droplets or airborne should be initiated only after extensive experimental or simulation-based studies and research. Aerobiology is the study involving aerial diffusion, biological material deposition, and aerosolization (Pepper & Dowd, 2009). Unlike droplet transmission, individuals are susceptible to airborne particles by inhalation or close contact with secondary infectious sources (VG et al., 1993). Disease-carrying droplets so far have proven to be contagious within a radius of approximately 3 -feet from the infectious source (WELLS, 1934). In enclosed or indoor spaces, the potential threat of infection caused by respiratory and nuclei droplets is considerably high since the velocity, which is dictated by the mass aids in trapping onto surfaces at various distances from the source

(Cole & Cook, 1998). In addition, as outlined by (Gralton et al., 2011), Individuals at a distance from the source are also at a high risk of exposure to airborne particles.

Isolation wards/rooms or negative pressure rooms are mainly designed to control the contamination due to airborne and droplet transmission mentioned above. One of the main causes of developing a positive or neutral ventilation pressure gradient is the action of door-opening and closing of the AIIR (Saravia et al., 2007). A comparative study carried out by (Adams et al., 2011) compared the contaminant containment efficiency of AIIRs using fluorescent microspheres as infectious droplets. It was identified that air traffic caused by healthcare providers reduced the suppression efficiency of droplets. AIIRs provided with anterooms, however, limited the net particle escape during the action of door-opening and closing and thus mitigating hospital-acquired infections (HAIs) for inpatients. The latest studies related to isolation rooms and mechanical ventilation are intended to find effective methods of controlling contaminated air inside AIIR and between the outer environments. Most of these studies are aided by software implementing Computational fluid dynamics (CFD). An analysis completed by (Khankari, 2017) used a 3-dimensional CFD model of a typical isolation room. The impact of HVAC designs on thermal comfort, airflow patterns, and velocity was determined using CFD simulations employing airflow patterns, PMV distribution, temperature distribution, and flow path lines within the room. The study concluded that the case where the supply diffuser is above the patient's head and the return grill behind the supply diffuser offered the best path for infectious particles to exhaust out of the return air grill without causing considerable recirculation.

The implementation of novel ventilation configurations in an isolation ward is the main objective of this study. In a typical displacement ventilation model, a thin layer of air is developed above the ground due to the floor supply and the relatively hot contaminated air rises and mixes with the ambient air due to its higher energy and less density (Ren et al., 2015). Stratum ventilation is a concept that is developed to primarily cater for elevated room temperature and undesired thermal comfort. This configuration is designed in a way that the occupant zone is subjected to horizontal fresh air supply and return (Lin, 2017). Curtain–air–jet configuration is also a potential improvement for ventilation performance in AIIRs. While the primary objective of implementing air curtains is to separate the contaminated zone from the clean zone, several other benefits such as reducing or balancing the cooling requirement in a healthcare environment are also achieved by air curtains. The study uses these configurations to improve a base configuration of an isolation ward using ANSYS -Simulation-based conclusions.

2. MATERIALS AND METHODS

Local survey results

Figure 1 represents the HVAC plan of isolation unit A obtained from the survey conducted locally. The isolation room is a 4–bed patient ward with an anteroom. The dimensions of the isolation room are 6.9 x 5.6 x 2.6 m.

Indices for quantification

1. Air exchange efficiency (ε_a)

As the name implies, it measures the efficiency between the predicted air replacement time and the actual age of air in the space. It measures the ratio between the shortest path possible for air replacement in a time reference (τ_n) and the actual time needed for air exchange (τ_{exe}) as shown in the equation below.

$$\varepsilon_a = \frac{\tau_n}{\tau_{exe}} \qquad (1)$$

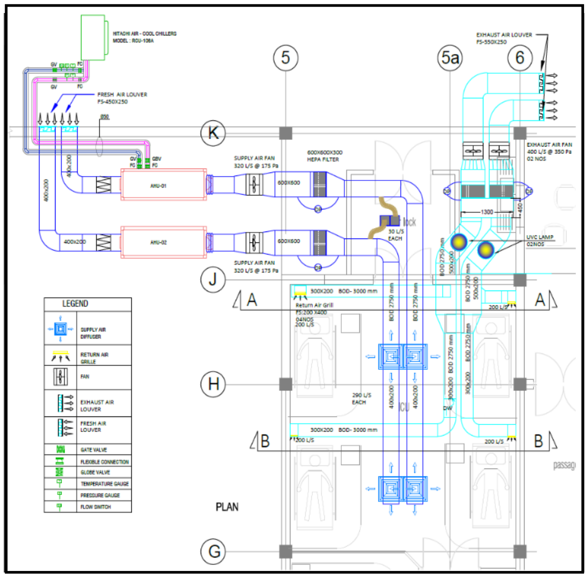


Figure 1 - HVAC Plan of Isolation unit A (Source – survey ABANS

2. <u>Air exchange efficiency (ε_a)</u>

As the name implies, it measures the efficiency between the predicted air replacement time and the actual age of air in the space. It measures the ratio between the shortest path possible for air replacement in a time reference (τ_n) and the actual time needed for air exchange (τ_{exe}) as shown in the equation below.

$$\varepsilon_a = \frac{\tau_n}{\tau_{exe}} \qquad (2)$$

It is identified that the shortest possible time for air replacement (τ_n) is the inverse value of the air exchange rate in the space which is given by the following formula.

$$\tau_n = \frac{V}{Q} \qquad (3)$$

Where V is the volume of the indoor space and Q is the ventilation flow rate.

- Mean age of Air -MAA ($\bar{\tau}$)

As defined by (Simons et al., 2016) mean age of air refers to the time air has spent in a space or a point in the space accumulating potential contaminants. It is defined that the actual time needed for air exchange, τ_{exe} is twice the value of the mean age of air in the room, $\bar{\tau}$. Hence, obtaining the mean age of air through CFD simulations enables the calculation of air exchange efficiency which is one objective of this study. In conclusion, air exchange efficiency in this study is calculated using the combination of Equations 1 and 2 as shown below.

$$\varepsilon_a = \frac{\tau_n}{\tau_{exe}} = \frac{V/Q}{2\,\bar{\tau}} \qquad (4)$$

3. <u>Contaminant removal effectiveness ε_c</u>

In contrast to ventilation efficiency, contaminant removal effectiveness is an indicator based on the contaminant concentration at the exhausts, C_e to the average contaminant concentration in the indoor space $\bar{C}$ ("ASHRAE_Standard62-01_04_," n.d.) as shown in the following formula.

$$\varepsilon_c = \frac{C_e - C_s}{\bar{C} - C_s} \tag{5}$$

Here, C_s refers to the contaminant concentration at the supply which is usually considered as 0 in negative pressure isolation rooms analysis. This parameter is applied in this study using the plane basis approach where the average contaminant concentration in the breathing plane of healthcare workers (HCWs) is taken as the indoor space concentration.

CFD Simulation Setup

<u>Solid Works Model</u>

The Simulation study is carried out in ANSYS to improve the mechanical ventilation efficiency of the base configuration that was modelled using SOLIDWORKS as shown in figure 2.

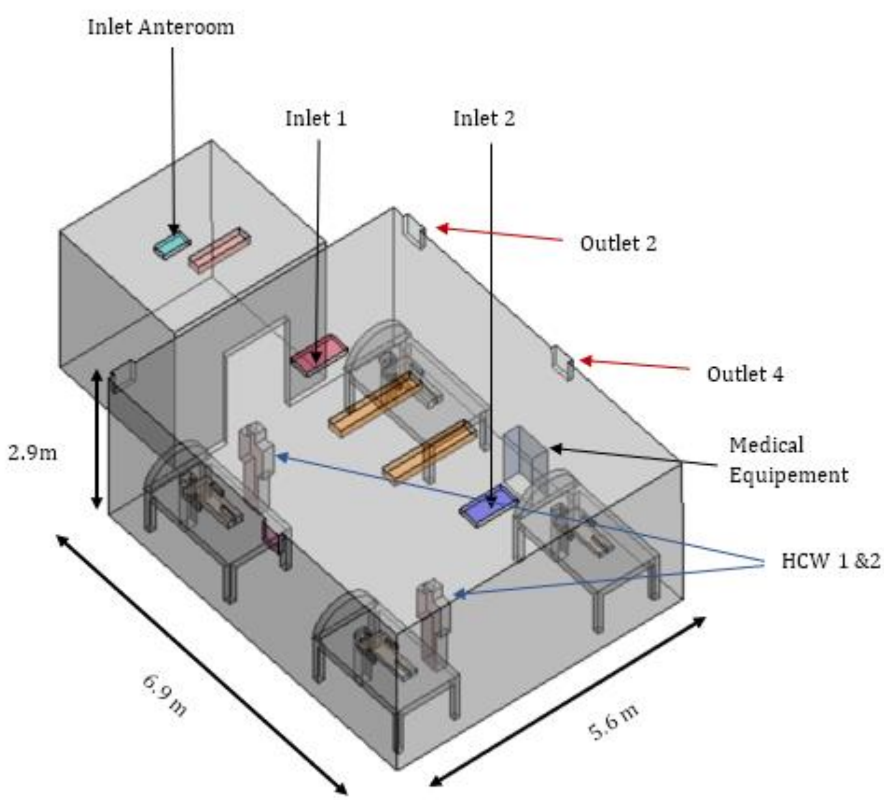


Figure 2 - Isolation unit A- 3-D geometry Model

The proposed design also includes the Anteroom for accurate simulation of airflow patterns in cases where the door room is unintentionally kept open. In addition to the components illustrated in the HVAC plan, the 3-D isolation unit also consists of models representing 4 patients, 2 healthcare workers, lamps, and medical equipment. Three ventilation configurations are suggested in view of improving the ventilation performance of the base configuration based on the analyzed indoor air quality indices and other vital measures.

Ansys Boundary conditions

The simulation study is carried out in both ANSYS – CFX and FLUENT. The air change efficiency ε_a is obtained via ANSYS -CFX using an "AgeOfAir" variable. The expression was turned on in the continuous fluid model. The age of air was calculated by specifying the age of air at the inlet to be 0. Then, a subdomain was created as the source term for the analysis and the age of air was increased by 1 second. The table below shows the initial condition for each ventilation configuration used in ANSYS -CFX.

Table 1- Boundary Conditions Ansys CFX solver

Boundary Conditions – CFX –Pre			
Mass flow Inlet	**Applicable Case**	**NOS**	**Value**
	Base case	2	0.362 kg/s
	Case-1-Displacement ventilation	4	0.181 kg/s
	Case-2- Stratum ventilation	2	0.362 kg/s
	Case-3- Air-jet -curtain	2	0.362 kg/s
Exhaust Outlet	Base case	4	-6 Pa
	Case-1-Displacement ventilation	4	
	Case-2- Stratum ventilation	4	
	Case-3- Air-jet -curtain	4	
Velocity inlet	Case-3- Air-jet -curtain	4	0.5 m/s, 1 m/s

The simulation carried out in ANSYS-FLUENT was utilized to obtain the contaminant removal effectiveness and several other vital results which aided in evaluating efficient ventilation configurations. The following tables represent the boundary conditions used for the simulation study in ANSYS – FLUENT.

I. Initial conditions

An airflow velocity *of 0.617m*/s for the two inlets in the isolation space and *0.24m/s* supply for the anteroom diffuser is created using the values obtained from the HVAC Plan. All four exhausts in the domain are designed as pressure – outlets in order to generate the target value of negative pressure in the room which is -5pa compared to adjacent spaces.

Table 2 - Boundary Conditions- Fluent Solver

Boundary conditions				
Type	**Geometry**	**Temperature (K)**	**Velocity Magnitude (m/s)**	**Gauge Pressure (Pa)**
Inlet	Inlet (1 and 2)	288	0.62	0
	Inlet - Anteroom	288	0.24	5

	Patient Mouth	315	1.30	0
Outlet	4 Pressure Outlets	300	N. A	-6
	Geometry	**Temperature(K)**	**Heat Flux(W/m²)**	**Convection**
Walls	HCW	309	60	N. A
	Manakin	315	60	N. A
	Lamps	320	160	N. A
	Medical equipment	305	149	N. A
	Wall solid	N. A	N. A	14.7

II. DPM Boundary conditions

Discrete phase particles in the continuous fluid domain should be assigned with particular behaviour in the vicinity of certain boundaries in order to simulate accurate tracks and obtain results that depict the real condition in such environments. Table 3 shows the DPM boundary conditions used for simulations.

Table 3 - DPM Boundary conditions – Ansys Fluent

Property	Type /value	
Injection type	Surface	
Surface options	Face normal direction	
Material	Carbon -dioxide	
Particle type	Inert	
Velocity Magnitude	1.3 m/s	
Total flow rate	4.183×10^{-4} kg/s	
Particle treatment	Unsteady	Interaction with continuous phase

The two supply inlets to the isolation room are assigned with a DPM boundary of "reflect" to ensure that exhaled particles do not leave the domain through any air supply inlet. Patient manikins, HCWs, medical-equipment, lamps, and walls are modelled as DPM boundary of "trap" to attach particles upon contact. "Escape" condition is used for patient mouth and exhausts to ensure particles in these boundaries escape in the direction specified.

Suggested Ventilation configurations

I. Displacement Ventilation

The two supply diffusers in the base modal are replaced by 4 diffusers with cross-sections of 0.4 x 0.4m using a lower flow rate in view of reducing the inlet velocities. This is done in order to sweep contaminated air surrounding the patient and HCWs to the 4 exhaust vents on the ceiling without causing induction or air mixing. Two supply diffusers are placed on the west wall of the room while the remaining are placed on the entrance wall as shown in Figure 3.

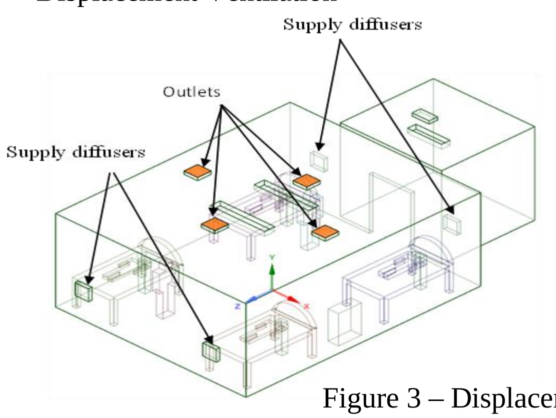


Figure 3 – Displacement Ventilation

II. Stratum Ventilation | Curtain - Air- jet Ventilation

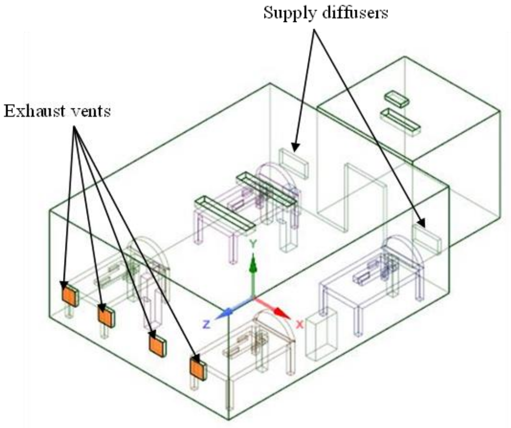


Figure 5 – Stratum Ventilation

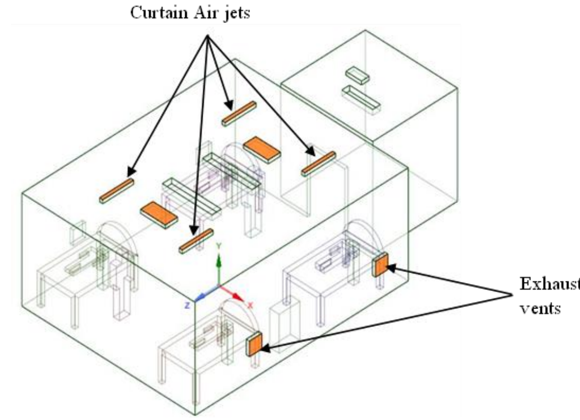


Figure 4 – Curtain Air-Jet Ventilation

Stratum ventilation is a novel technology that targets only the occupied zone of an indoor environment. A stratum ventilation system mainly addresses thermal comfort, energy consumption and efficiency, and indoor air quality (IAQ). In the geometry shown in Figure 4, four exhaust vents are placed at the west wall of the isolation room, elevated just above the breathing plane of all 4 patients. The two supply diffusers are placed on the east wall (Entrance boundary wall) above the patient bed. In the Curtain air-jet model shown in Figure 5, the AII room is modified by adding 4 Air-jet curtains with a (1 m x 0.1m) cross-section on the ceiling in line with the available gap between the patient and the still position of HCWs. The supply diffuser size and location of the base geometry are unchanged to ensure sufficient airflow and cooling in the room.

4. RESULTS AND DISCUSSION

Grid Independence Test

Parametric analysis is carried out by defining Edge sizing for selected geometries and using the type of definition to be "Number of divisions" as the input parameter in ANSYS Mesh. Results variation for Volume- weighted- mean- velocity is calculated in the volume inside the solid boundaries of the geometry whereas Average -facet – velocity is calculated using the variations observed on the faces of each assigned exhaust. The convergence test results are plotted below.

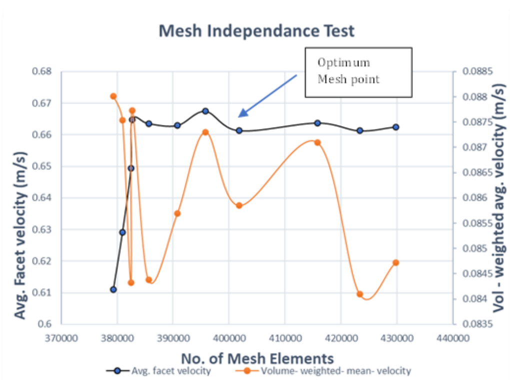
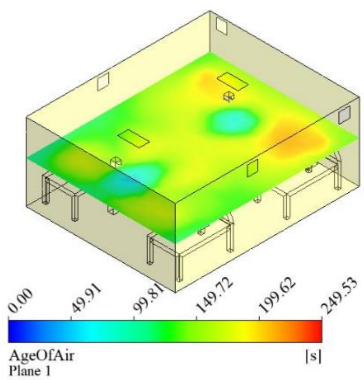


Figure 6 - Grid Independence test results

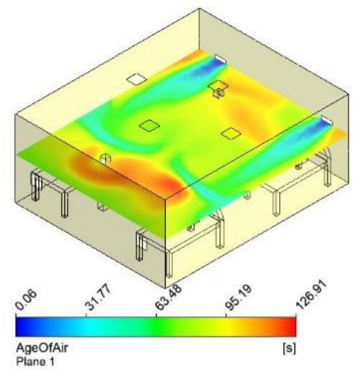
For a volume-weighted study, refinement in geometrical edges does not provide accurate improvements as expected. The optimum mesh size of 401809 elements with 78069 nodes is chosen for future simulations.

Air change efficiency

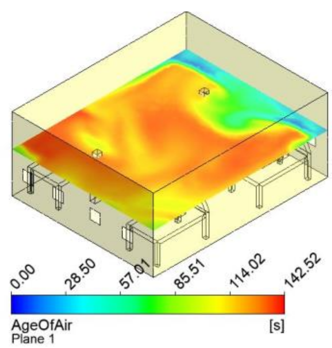
A steady-state simulation was carried out in ANSYS- CFX for each suggested ventilation configuration including the base model. The resulting age of air plots on the health care worker breathing plane is shown in the following figures.



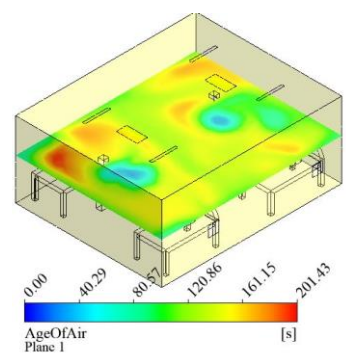
A) Base Model



B) Displacement Ventilation



C) Stratum Ventilation



D) Curtain -Air -jet ventilation

Figure 7 – Age of Air contour plots HCW breathing plane

In Figure 7 A), the age of air in the region of each patient mouth is considerably high compared to other regions of the room. This may increase the chances of possible accumulation of exhaled infectious particles in those regions. A potential stagnation region with 180 – 220s age of air (Orange colour) is created near-patient 2. This could happen due to air recirculation combined with exhausts unable to draw supplied air through a laminar flow. In contrast, case 1 in Figure 7 B) employing a displacement ventilation configuration exhibits a maximum age of air of only 128 seconds compared to the base model that yielded 249 seconds. Potential infectious particles exhaled from either patient 1 or 2 will be swept away in less than 50 seconds as observed in the colour bar shown in Figure 7 B). However, it is observed that a relatively low diffusive region occurs between patients 3 and 4 resulting in an open cavity like behaviour. (Lawson & Barakos, 2011) . Such regions are undesirable in the context of contaminant suppression. In contrast, one major advantage of the stratum ventilation configuration is that fresh air tends to continuously concentrate on the anteroom door region. Beyond this region, the age of air constantly lies between the range of 100 – 125 seconds (See Figure 7 C)). This regular age of air in the vicinity of HCW s and patients could diminish any zones of recirculation. Figure 7 D) is a representation of the curtain air-jet model with 0.5m/s air jet velocity. In contrast to an air jet velocity of 1m/s, the current configuration is capable of improving the age of air in the HCW breathing plane.

The table below represents the mean age of air obtained from ANSYS -CFX POST and the calculated air change efficiency of each corresponding configuration.

Table 4 – Summary – Mean age of air and Air change efficiency

	Configuration			
	Base Model	**Displacement Ventilation**	**Stratum Ventilation**	**Air -jet Curtain**
Mean age of Air (s)	172.3	76.3	91.7	133.2
Air change Efficiency (ε_a)	0.503	0.568	0.946	0.505

Contaminant removal effectiveness (ε_c)

Contaminant removal effectiveness can be obtained via several methods depending on the region of interest. Where there is a specific region or an area considered on the domain relative to the exhaust concentration, it is then referred to as the local contaminant removal effectiveness. Where there is no such location specified, it is referred to as the global contaminant removal effectiveness. The local contaminant removal effectiveness was obtained using the facet average on the exhaust and the HCW breathing plane.

Table 5 – Results - Global contaminant removal effectiveness

Ventilation Strategy	**Area weighted avg exhaust (x1000) (kg/m^3) (x10^3)**	**Volume Avg contaminant concentration (kg/m^3) (x10^3)**	**Contaminant removal effectiveness**
Base	0.036	0.149	0.243
Displacement	2.915	1.258	2.317
Stratum	0.929	0.677	1.371
Air jet	0.977	0.612	1.596

The mixing ventilation strategy implemented in the base model resulted in a low ε_c value of 0.243. This depicts that the contamination source and HCW breathing plane is in the zone of air circulation and hence increased the risk of direct exposure to exhaled contaminant particles. In contrast, each of the suggested configurations represented the upper limit ($\boldsymbol{\varepsilon_c} > 1$) of the characteristic flow type for contaminant removal effectiveness and thus reducing the exposure to potential contamination by occupants in the facility.

Identifying correlations between air change efficiency and contaminant removal effectiveness enables accurate prediction of exhaled particle behaviour in the design stage of an AII room. Figure 8 represents the correlation between the two IAQ indices.

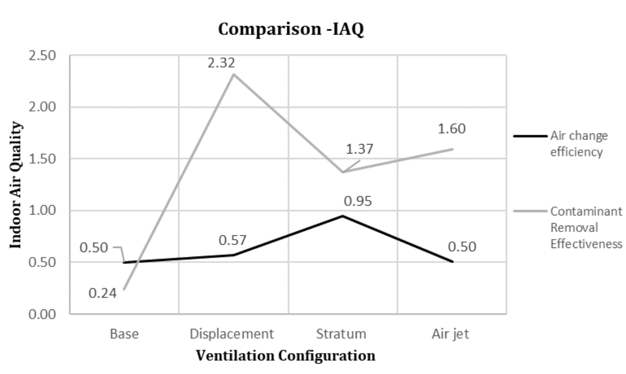


Figure 8 - Comparison of obtained indoor air quality indices

The base model, which represented a perfect mixing model with ε_a of 0.503, have also resulted in the lowest contaminant removal effectiveness of 0.252. Although similar mixing ventilation configurations are required to validate this statement, the CFD study carried out by (Novoselac and Srebric 2003) has also provided factual results highlighting that an increase in air change efficiency, ε_a for a mixing ventilation system is directly followed by an increase in contaminant removal effectiveness as underlined in the current study. Such a correlation is not noticeable in other ventilation configurations namely, displacement and stratum where the air change efficiency is 0.568 and 0.946 respectively. Based on these results, developing correlations by equations or specific criteria solely based on these two tools is therefore considered unsuitable.

Exhaled particle tracking

Exhaled particle tracking was carried out using the DPM boundary conditions shown in Table 3. A time-based approach is used for each path line model. This approach in contrast to a domain length-based approach will provide more clarity when comparing each ventilation configuration since particle residence time with reference to its relevant position is vital in AII rooms.

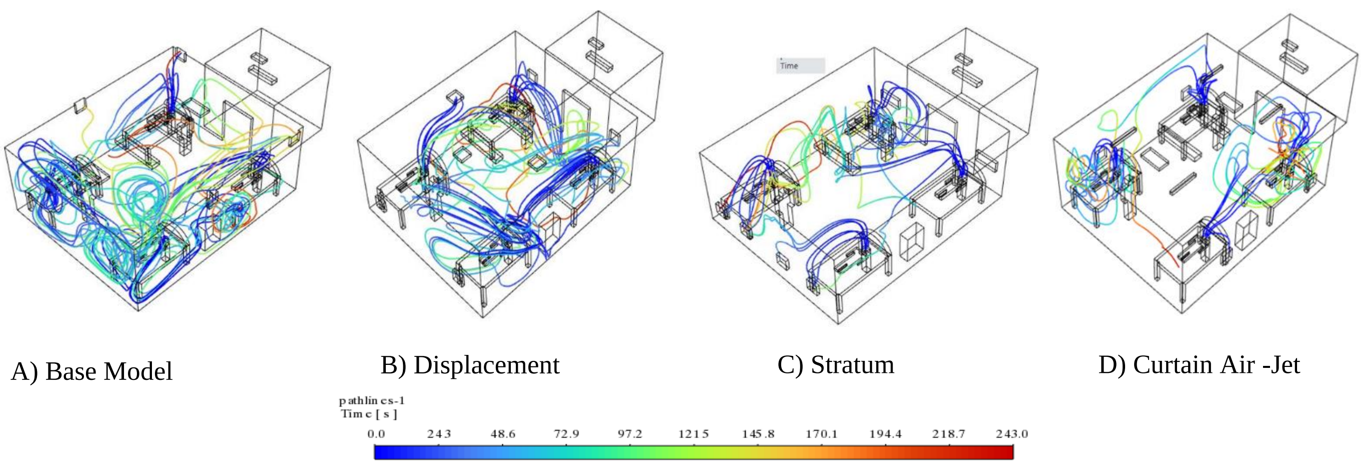


Figure 9 – Exhaled particle tracking – Path line models

In the base model in Figure 9 A), pathlines surrounding HCW 2 is entrained in the supply air current entering the domain from supply inlet 2. Particle circulation is therefore dominant in this region for a time range of approximately 0 – 96 seconds. In the displacement ventilation model shown in Figure 9 B), it is observed that exhaled particles from each patient except for patient 3 reside at a lower level upon exhalation. It is considered beneficial when the airborne contaminant particle density is less than the room air density (*Engineering Guide Displacement Ventilation*, 2016a). The capability of upward motion of contaminants is strictly affected by its relative density. Since the exhaled CO_2 particle density is higher than the surrounding air density, contaminant escape efficiency is reduced in this model. In stratum ventilation, it is observed that HCW 1 is surrounded by newly released particles from patient 1 or 2. One possible flaw of this configuration is that exhaled particles of patients 1 and 2 do not reach the outlets in a streamlined path. However, the characteristic of stratum ventilation has been able to avoid two of the main challenges faced in AII rooms, namely: Air short-circuiting and Stagnation. (Lin et al.,2009) . In comparison with the simulation study results by (F. Wang et al. 2021), which concluded that a curtain air jet velocity of 0.5 m/s is best suited for contaminant containment, the current study also indicates better ventilation with a 0.5 m/s air jet velocity as seen in Figure 9 D).

Figure 10 summarizes the escaped particle efficiency for each configuration in the simulated time frame of 4 minutes.

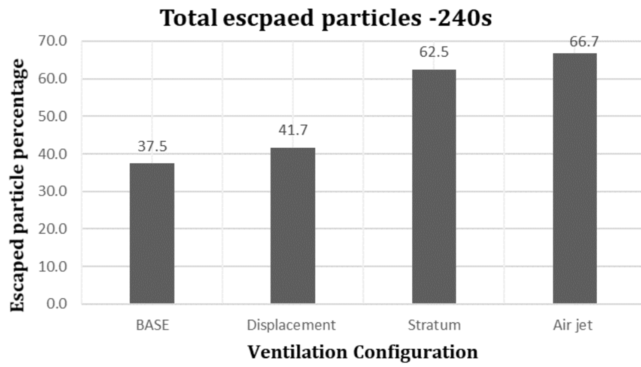


Figure 10 - Total escaped particle percentage

Temperature and Pressure distribution

The practical suitability of these configurations can be evaluated by analyzing the average temperature and pressure values as shown in the figures below and comparing them against specified values by guidelines.

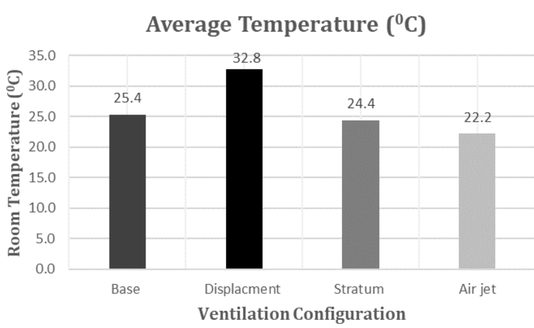


Figure 11 – Temperature Distribution of each ventilation configuration

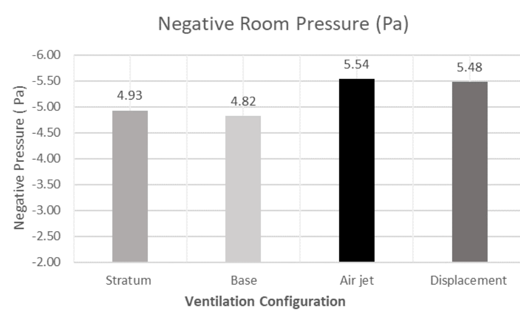


Figure 8 - Pressure differential of each ventilation configuration

ASHRAE Standard implemented guideline ("Engineering Guide Displacement Ventilation" 2016) specifies a temperature of 68F or 20^{0}C for the supply air temperature. Furthermore, it is specified that a displacement ventilation configuration with floor-level supply is most efficient when *'contaminant particles are warmer and lighter than the supplied air'*. Although exhaled particles are significantly warmer than the supply air, their higher density makes them heavier compared to the continuous airflow. This can be concluded as the pivotal factor for the increased temperature in the AII room. It should be noted that although Anteroom airflow can reduce the pressure differential, it is not capable of regulating the AIIR pressure towards a positive pressure. Therefore, it is predicted that AIIR differential pressure could be slightly higher when the Anteroom door is closed.

5. CONCLUSIONS

The main objective of this study was to support the ongoing multi-disciplinary efforts of understanding particle behaviour in isolation wards to minimize the spread of infectious airborne diseases. Air change efficiency values of both displacement and stratum ventilation configurations showed unidirectional flow characteristics while the base model showed a perfect mixing flow type.

Results revealed that there is negligible to no correlation between the two indices and possible correlations could exist only within a specific type of ventilation strategy. Furthermore, path line models showed that total escaped particles efficiency was significantly improved by 25 % and 30 % in both stratum and curtain-air-jet models respectively compared to the base model. Finally, these two models could maintain a room temperature in the region of 21 – 25 ^{0}C and negative pressure of -5 Pa as required by the original configuration confirming their suitability for actual operation.

6. ACKNOWLEDGEMENTS

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