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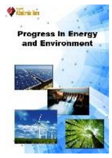

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Original Article

A CFD assessment on ventilation strategies in mitigating healthcare-associated infection in single patient ward

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Abstract

A promising ventilation strategy is an effective measure to enhance indoor air quality and protect the patients against healthcare-acquired infection. The Computational Fluid Dynamics (CFD) model represents a patient ward that was constructed using Computer-Aided Design (CAD) software. The simulated results were verified and validated based on the published data. A Renormalization Group (RNG) k-ε model based on the Eulerian approach was used to simulate the airflow turbulence, while a discrete phase model (DPM) based on the Lagrangian approach was used to predict the dispersion of airborne particles. This study examined four cases of ventilation strategies, with varying ventilation rates, positioning of supply air diffusers, and location of exhaust grilles. This study revealed that the installation of air curtain jet coupled with a ceiling-mounted air supply diffuser (case 3) above the patient-occupying zone has the highest wiping efficiency against the infectious particles. The utilization of ventilation strategy in case 3 managed to reduce the particle by approximately 3.3 times as compared to the baseline case. The study outcome also suggested that the exhaust grilles should be placed on the upper wall, to ensure a proper mixing of fresh air in the entire patient ward.

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1 Introduction

Healthcare-associated infections (HAI) remained one of the dominant threats among admitted patients. Between 1975 and 1995, the rate of HAI per 1,000 patient days increased by 36% [1]. HAI is also the sixth most common cause of death in acute care hospitals, with an estimated 90,000 fatalities each year directly attributable to it [2]. In 2011, Magill, Edwards, Bamberg, Beldavs, Dumyati, Kainer, Lynfield, Maloney, McAllister-Hollod, Nadle, Ray, Thompson, Wilson and Fridkin [3] reported that approximately 648,000 hospitalized patients suffered 721,800 HAIs, according to the multistate point-prevalence survey in the US. The Centers for Disease Control and Prevention estimated that 1.7 million of HAIs and 99,000 associated fatalities yearly [4]. Later, about 2 million cases of HAI are reported each year in the US, according to estimates [5]. In 2018, it was estimated that 3% of hospitalized patients in China had HAIs and more than 500,000 of these infections occur in intensive care units (ICUs), most are linked to the use of intrusive equipment such as ventilators or central venous catheters [6]. In recent years, airborne infection emerged as a significant concern in healthcare facilities, due to the novel coronavirus outbreak. This is a highly infectious disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and resulted in more than 6.8 million deaths [7]. Airborne infections are caused by tiny pathogenic particles that can remain suspended in the air and be transmitted over long distances, ended up inhaled by a susceptible individual. Looking at the catastrophic effects of the infections, it is essential to develop more intervention strategies in suppressing the infection risk [8].

Several known factors could affect the fate of these pollutants including the ventilation layout, air change rate, source of pollutants, and human movement effects [9-11]. Satheesan, Mui and Wong [11] indicated that the location of the infected patient is critical in determining the range of infection risk to other ward occupants. The research team also revealed that increasing the air change rate does not necessarily reduce the exposure risk towards the infectious particles. Dao and Kim [12] emphasized that air supply and exhaust grilles should be properly designed to allow inlet air stream removing the pathogenic particles around the patient to the outlet. led to an increase in the velocity of the airflow in the room. Le, Nguyen and Kieu [13] suggested that changing the location of the exhaust air grilles could improve the ventilation performance in an airborne isolation room. Research also showed that human movement or sliding door motion could adversely impact the air velocity, pressure field and contaminant distribution, within general ventilated or specific negative pressure isolation rooms [14-16].

An air curtain is made up of a fan unit that creates a barrier against things like heat, moisture, dust, odours, insects, and more. The generator is often situated above the door and blows the curtain down vertically when it comes to cold store air curtains. While most air curtains do not, some do so via a return duct located opposite the air jet output [17]. Implementation of air curtain will cause separation of two environments without restricting the opening access of these environments [18]. The sealing of cold storage room entrances [19], the apertures of refrigerator display cabinets [20], and smoke confinement [21] are the common applications of air curtains in pollution management. Instead of taking up as much room as vestibules and obstructing traffic, air curtains limit infiltration. They have been around for around 50 years and have their roots in a patent that Van Kennel filed in 1904 [22]. In healthcare facilities, air curtains are used in the Protected Occupied Zone Ventilation (POV) and Protected Zone Ventilation (PZV) techniques, which function well in blocking the airborne transmission pathway, thus lowering the HAI risk. It is discovered that the protection efficiency varies from 8% to 50% based on the source air velocity, exhaust location, and partition usage [23]. Cao et al. discovered that the dimensionless concentration was 40% less than for fully mixed ventilation when the supply air velocity was increased to 4 m/s in the downward plane jet [24]. These investigations also revealed that several factors, such as supply velocity, ejection angle, and room geometries, affect how well air curtains isolate the pollution emissions [24]. According to Wang, Chaerasari, Rakshit and Permana [25], an air-jet curtain with an operating velocity of 0.5 m/s has the highest efficiency at lowering contamination to a background level below 400 ppm and minimizing exposure to aerosol particles produced by coughing patients. Within the isolation room, it is capable of maintaining the pressure differential specified at 8 Pa. Additionally, it is anticipated that using an air-jet curtain will improve the security of the isolation room's medical staff. Another study conducted by Ye et al. [26] show that an air curtain could decrease 70% to 90% of average pollutants mass fraction sourced from patient's exhalation activity in a consultation room.

Previous studies have demonstrated the competence of using an air curtain in providing a protective zone for the immunocompromised patients. Meanwhile, several studies showed that implementing a unidirectional airflow breathing approach reduced the patient's risk of developing HAI [27]. However, the efficiency of using a combination of a unidirectional air supply diffuser and air curtain in a patient room remains unclear and warrants further studies. On the other hand, the different placement of exhaust grilles in patient ward could affect the particle concentration within the critical area of patients. Therefore, this study aims to examine the ventilation arrangement of air curtain, ceiling-mounted air diffuser and exhaust grilles in reducing particle concentration in the vicinity of the patient. The number of particles settled around the patient was used to evaluate the effectiveness of the ceiling-mounted air curtain, where a smaller number of deposited particles indicated an efficient ventilation system. Present finding could help engineers and designers in deciding the optimal ventilation layout for a single patient ward.

2 Methodology

2.1. Description of the CFD model of a patient ward

Fig. 1 showed a CFD model of a patient ward constructed using Computer-Aided Design (CAD) software, with labelled components. The patient ward has a dimension of 4.00 m (L) × 2.50 m (W) × 2.65 m (H). Two upright-standing healthcare workers were involved in the present study, one of them (beige colour) was assumed to be infected with the infectious disease and released the bacteria-carrying particles (BCPs). Another healthcare worker (blue colour) was assumed to be a healthy worker and does not release any BCPs. Meanwhile, the manikin (green colour) lying on the bed is representing the patient. For the baseline case study, clean air was supplied into the room through the air curtain jet with an effective surface area of 0.10 m^2. Then, the airborne contaminants were extracted via the two exhaust grilles (pressure outlet) that were placed at high wall locations, each with an effective area of 0.02 m^2.

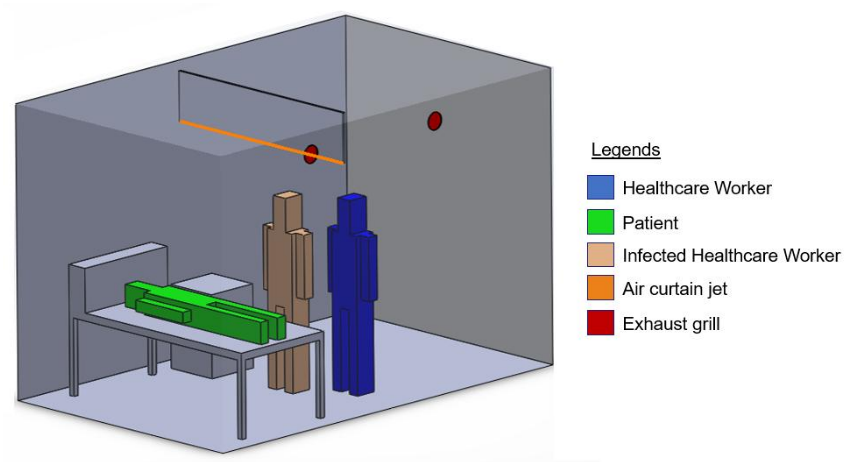


Fig. 1 The CFD model of the patient ward under baseline case ventilation strategy.

2.2 Grid independence test

In a CFD analysis, insufficient grid density could yield an under/over-predicted result [28]. To make sure that the numerical errors in the simulated results are insignificant, a grid-independent test (GIT) was carried out [29]. GIT is a method used to identify the ideal grid condition that contains the fewest grids while producing a converged and reliable simulated result. GIT has been used in numerous CFD studies. However, there is no standard application procedure available. Most studies rely on the researcher's experience in choosing the grid settings and the verification test for selecting the optimum grid density [30]. In the present study, Grid Convergence Index (GCI) was calculated to evaluate the numerical error due to different sets of grid densities. GCI is a relative error bound that describes the variation of solutions with mesh refinement [31]. Volk et al. claimed a GCI value of less than 10 % could be considered acceptable [32]. A thorough GIT work was performed in authors' previous work [33]. As demonstrated, 6 million tetrahedral are proven sufficient to achieve grid independence (GCI = 4.3%) and convinced to produce precise simulated result. The further refinement to 12 million mesh only contributes to a negligible improvement of prediction accuracy (0.8%) and does not attain the computational efficiency.

2.3 Airflow turbulence and discrete phase models

According to our previous validation work, an RNG k-ε model was proven to be more reliable in predicting the indoor airflow velocities in low turbulence healthcare facilities [29], as compared to Reynolds-Averaged Navier-Stokes (RANS) models such as standard k-ε, realizable k-ε, and SST k-ω. The validation work shows a good agreement with previous studies, with a relative error of less than 10 % [11]. In this study, the RNG k-ε model was used to simulate the airflow turbulence in the patient ward. The general governing equations can be expressed as in Eq. (1) [34]:

$$\frac{\partial(\rho\Phi)}{\partial t} + \nabla \cdot (\rho \Phi V) = \nabla \cdot \left(\Gamma_{\varphi} \nabla_{\varphi}\right) + S_{\varphi} \quad (1)$$

where ρ is the air density, V denotes the air velocity vector, φ is the general variable that represents the velocity component (u,v,w), $\Gamma\varphi$ is the effective diffusion coefficient of φ and $S\varphi$ are the source terms.

Meanwhile, a DPM based on the Lagrangian approach was used to track the trajectories of human-emitted particles. More detailed validation work on predicting particle dispersion could be found in our previous study [35]. The stochastic discrete-particle technique was used to account for particle dispersion. By integrating each particle's motion, the turbulent dispersion of particles was modelled. The discrete random walk (DRW) model, a popular approach which included velocity fluctuations, was employed to simulate particle movement in this study [11]. Along with the stochastic behaviour of the surrounding turbulent flow, various forces (such as viscous drag, lift force, buoyancy, etc.) acting on the Lagrangian particles along their paths are considered [36]. The equation of particle motion is given by applying Newton’s second law [12], as expressed in Eq. (2).

$$\frac{\partial \vec{u}_p}{\partial t} = F_D\left(\vec{u} - \vec{u}_p\right) + \frac{g\left(\rho p - \rho\right)}{\rho p} + \vec{F} \quad (2)$$

where $\vec{u}_p$ is the particle velocity, F_D is the drag force, $\vec{u}$ is the fluid phase velocity, $\vec{g}$ is the gravitational acceleration, p_p is the density of the particle, p is the fluid density, $\vec{F}$ is an additional force.

Several main assumptions were applied in this numerical study. The air inside the patient ward is considered incompressible. Gravitational force, drag force, thermophoretic force and shear lift force were incorporated to produce a more realistic result [33]. For simplification, the respiratory activities of the human manikin are not included in the case studies. SIMPLE algorithm was employed for the pressure-velocity coupling in RANS equations. Second-order discretization upwind scheme was applied to solve convection and diffusion terms for flow variables. As recommended by Fluent [37], the convergence is achieved when continuity, x-velocity, y-velocity, z-velocity, k and ε reach 10^{-3}. Meanwhile, the residual monitoring of energy equation is set as 10^{-6}.

2.4 Description of case studies

The ventilation guidelines of healthcare facilities, as regulated in ASHRAE 170 offers some illuminating instructions regarding the ventilation rate in respective healthcare unit [38]. As per recommendation, the patient ward should fulfil the minimum requirement of 6 air change rate per hour (ach). For the baseline case study (case 1), the air curtain jet operated at 0.44m/s to fulfil such requirements. The value of ach could be calculated using Eq. (3) [39].

$$\text{Air change per hour, ACH} = \frac{Q}{V} \quad (3)$$

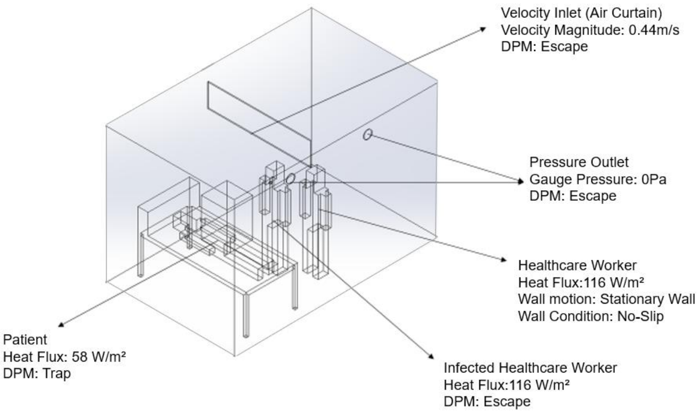
where Q is the volumetric flow rate of supplied air per hour and V is the volume of domain involved. The volumetric flow rate could be obtain using Eq. (4) [40].

$$Q = Av \quad (4)$$

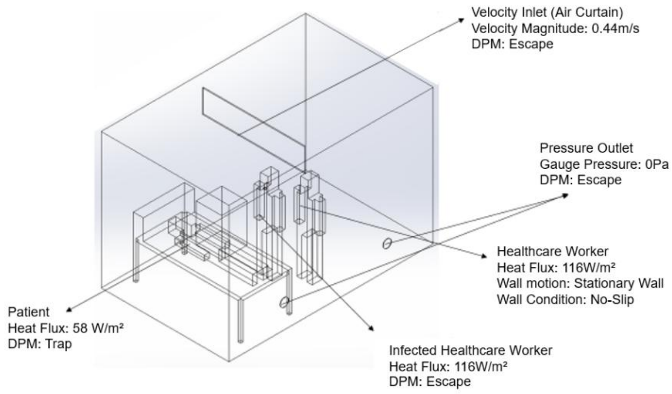
where A represents the effective area of supply air diffuser and v denotes the average velocity of supplied air.

A total of four case studies (case 1, case 2, case 3, and case 4) were conducted to examine the effect of ventilation layouts on the particle dispersion behaviour of human-emitted particles. For the subsequent case studies (case 3 and case 4), the ventilation configuration was varied by installing an additional ceiling-mounted diffuser with an effective area of 0.36m^2 which operates at 0.12m/s (6ach). For case 2 and case 4, the exhaust grilles were moved to the lower wall area where particles tend to accumulate over time due to gravitational effect. Humans were considered the source of heat flux in this study. An upright standing medical staff and a lying patient released the heat flux of 116 W/m^2 and 58 W/m^2, respectively [10]. The patient had a lower heat flux due to the assumption of minimal or no physical activity was performed [41]. The human manikins behave as stationary wall motion with no-slip wall condition. The infected healthcare worker released the bacteria-carrying particle at a rate of 1.31×10^{12} kg/s (equivalent to 600 particles/min) from the body surfaces. Xu et al. reported that SARS-

CoV-2 could survive on human skin for more than 9 hours and revealed that skin as the potential transmission vector of the disease [42]. Consequently, the skin particles shed by infected personnel, could be highly infectious. The released particles are assumed spherical with a diameter of 5 µm and density of 2.0 g/cm^3, similar to the representative pathogenic particle stated in previous investigation [43]. The DPM of healthcare worker, velocity inlets and pressure outlets were set to 'Escape' while the infected healthcare worker is set to 'Trap'. The "trap" condition assumed the particles did not accumulate enough rebound energy to overcome adhesion after colliding with the wall surface [33]. The description of the ventilation layout in each case study and its respective detailed boundary conditions were presented in Fig. 2 (a) to Fig. 2 (d), accordingly.



(a)



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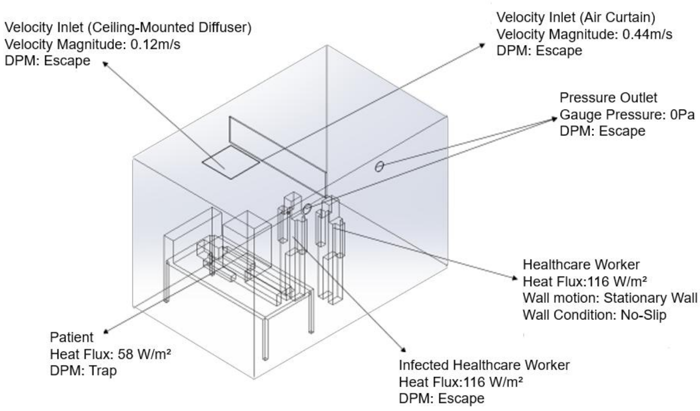

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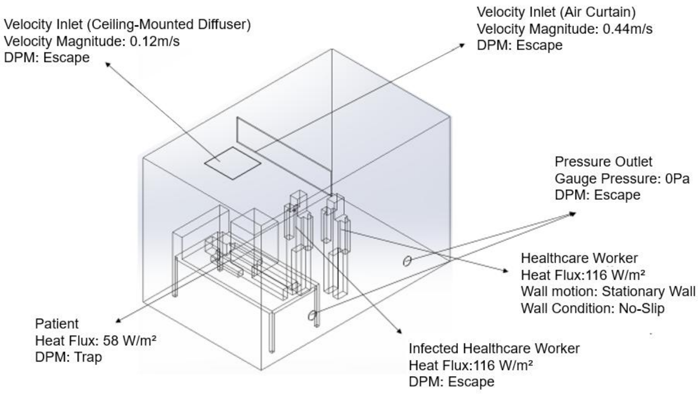

(d)

Fig. 2 The detailed boundary conditions applied to the CFD model in (a) case 1, (b) case 2, (c) case 3, and (d) case 4.

The summary of descriptions of the variation of ventilation layouts were presented in Table 1. Table 2 outlined the detailed boundary conditions applied to the computational domain.

Table 1 The description of velocity inlets and location of pressure outlets in each case study.

Case	Velocity inlets	Air change rate per hour	Location of pressure outlets
1	Air curtain jet	6	Upper wall
2	Air curtain jet	6	Bottom wall
3	Air curtain jet + Ceiling-mounted diffuser	12	Upper wall
4	Air curtain jet + Ceiling-mounted diffuser	12	Bottom wall

Table 2 Detail description of boundary condition.

Boundary Name	Boundary Type	Boundary Conditions
Air curtain jet	Velocity inlet	**Velocity Magnitude:** 0.44m/s **Direction:** Normal to the boundary
Ceiling mounted diffusers	Velocity inlet	**Velocity Magnitude:** 0.12m/s **Direction:** Normal to the boundary
Exhaust grilles	Pressure outlet	**Gauge Pressure:** 0 Pa
Infected healthcare worker	Wall	**Wall motion:** Stationary **Wall condition:** No-slip **Heat flux:** 116 W/m^2 **Mass flow rate:** 1.31 x 10^{12} kg/s (600 particle/min) **DPM:** Escape
Patient	Wall	**Wall motion:** Stationary **Wall condition:** No-slip **Heat flux:** 58 W/m^2 **DPM:** Escape

3 Result & discussion

The increment of the supply air diffuser and manipulation of the exhaust grille could impose considerable effects on the airflow distribution in a patient ward. Fig. 3 demonstrated the airflow velocity distribution that cuts through the plane YZ at x = 1.3 m, with vectors indicating the direction of airflow.

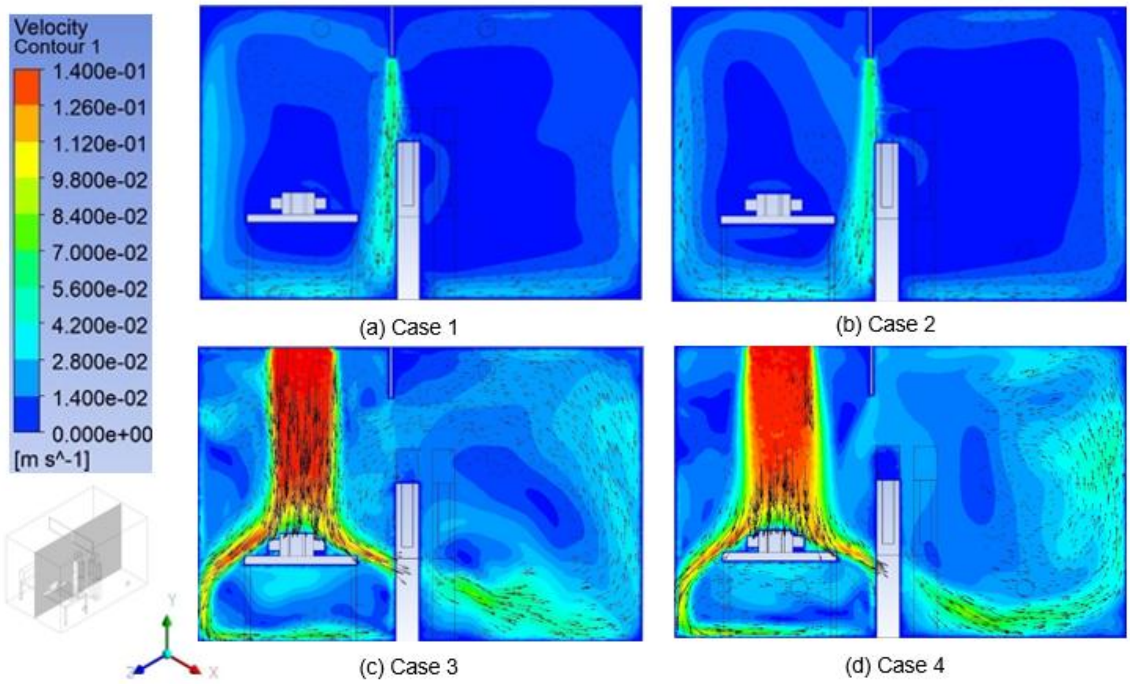

Fig. 3 The airflow velocity contour on plane YZ at x = 1.3 m for (a) case 1, (b) case 2, (c) case 3, and (d) case 4.

Comparing case 1 and case 2, the changes in airflow distribution were minimal when the position of the exhaust grille was moved to the bottom of the wall (near the floor region). However, when an additional ceiling-mounted air supply diffuser was installed, the airflow distribution in the ward varied significantly. As observed in case 3, the air supply diffuser supplied a higher airflow rate to the patient, with an air velocity of 0.12 m/s. Such an occurrence enhances the air change in the ward and promotes better air mixing in the entire ward. Meanwhile, in case 4, the active airflow region only increased at the right side when the exhaust grilles are located at the lower wall area though the same supply diffuser and ventilation rate are operated. Case 4 also demonstrated a greater magnitude of active airflow near the floor region.

Several infection-probability-based models correlated the particle concentration with the infection risk [44]. Theoretically, the higher the concentration of the infectious particle in the vicinity of the patient, the higher the tendency of a patient to contract the healthcare-associated infection. Therefore, the ventilation efficiency is subsequently examined by means of particle mass concentration. A lower particle concentration in the patient ward indicated that the ventilation strategy is effective towards removing the contaminant from the ward. Figure 4 displayed the particle mass concentration contour which cut through the XZ plane at y = 0.91 m for each case study.

A numerical investigation justified the air curtain jet as a promising strategy to reduce short-range transmission in a healthcare setting [45]. According to the simulated result in case 1, the particles dispersed by the infected healthcare worker did not penetrate the protective occupied zone provided by the air curtain jet. Therefore, the result could be claimed to concur with the previous findings which reported the air curtain jet reduced 70 % to 90 % of the average mass fraction of exhaled pollutants [26]. As shown in case 2, a higher concentration of particles accumulated at the back of the infected healthcare worker. The particle only spread at a longer distance as compared to case 1. This observation has indicated that the particle removal efficiency has decreased when the exhaust grilles are located at the lower wall region.

In case 3, the installation of an additional ceiling-mounted supply diffuser at the region above the patient increased the ventilation rate from 6 ach to 12 ach. Such a combination of supplied airflow greatly reduced the particle concentration and minimized the particle dispersion. A sufficient air change rate is important in diluting and removing indoor pollutants from the indoor environment [46]. Such favourable result reflected that the healthcare-associated infection risk could be lowered when installing the air curtain jet coupled with the ceiling-mounted air supply diffuser. The utilization of the ventilation strategy in case 3 managed to reduce the particle by approximately 3.3 times as compared to the baseline case. The highest particle concentration observed in case 1 was approximately 6×10^{-11} kg/m^3, while only 1.8×10^{-11}kg/m^3 in case 3 (on plane XZ at y = 0.91 m). This height was commonly monitored as that is the critical height that particle contamination could settle on a patient, subsequently causing infection. Moving to case 4, the particle dispersed further backwards and potentially contaminate the breathing zone of another healthcare worker. This phenomenon could be due to the intense airflow recirculation at the floor region, which encouraged the resuspension of particles to become airborne. When the exhaust grilles are positioned at the lower wall region, only the deposited contaminants could be removed. Consequently, the supplied fresh air could hardly reach the entire room and resulted in the accumulation of airborne particles in a stagnant airflow zone.

As evidenced by the better performance of the particle dilution effect in case 1 and case 3 compared to case 2 and case 4, it could be deduced that the exhaust grilles should be placed at the upper wall instead of the lower walls. Besides, the increment of ventilation rate using an additional air diffuser at the region above the patient could be practical to facilitate the removal of airborne particles.

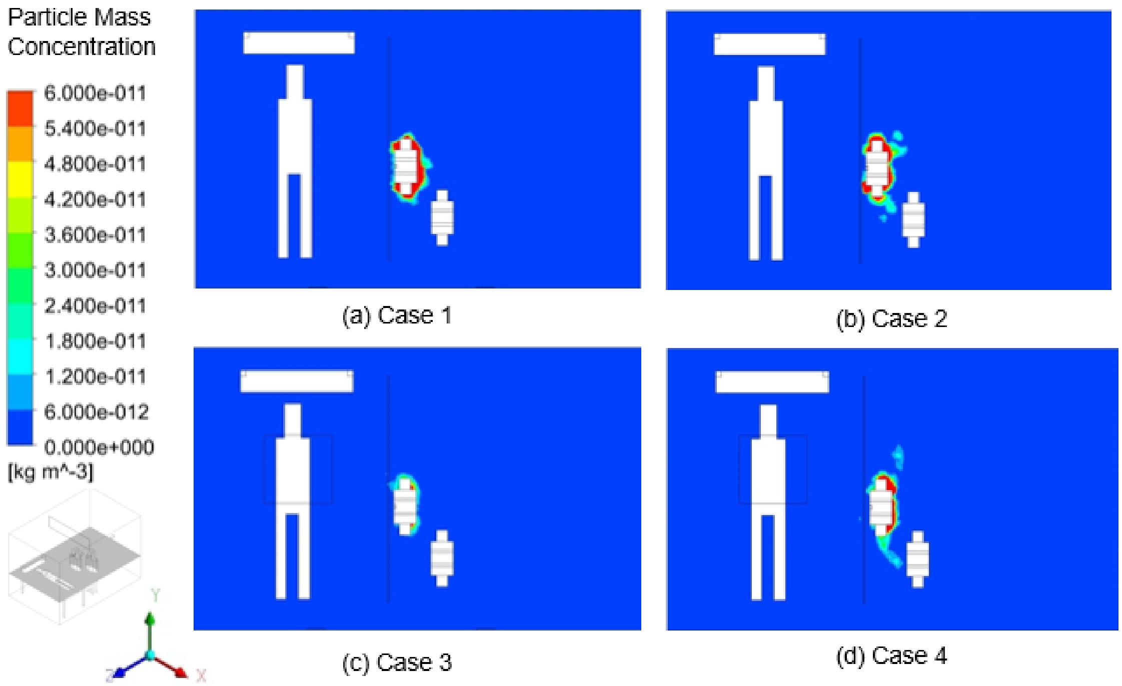

Fig. 4 The particle mass concentration contour on plane XZ at y = 0.91 m for (a) case 1, (b) case 2, (c) case 3, and (d) case 4.

4 Conclusion

The effect of ventilation layouts on the dispersion of human-emitted particles was examined using a CFD approach. The reliability of CFD results was verified and validated against the measurement data published in previous literature. The RNG k-ε model was employed to predict the indoor airflow characteristics, while the DPM based on the Lagrangian approach was used to trace the trajectory of each airborne particle. Present outcome agreed that air curtain is an effective ventilation strategy to prevent the infiltration of airborne contaminants. This study also revealed that both ventilation rate and ventilation layout were crucial factors in affecting the contaminant distribution in a patient ward. In this study, an air curtain jet coupled with a ceiling-mounted diffuser above the patient-occupying zone produced the greatest wiping efficiency against infectious particles. The present study also suggested the exhaust grilles should be placed on the upper wall, to ensure the mixing of fresh air in the entire patient ward. In future, transient studies (time-dependent) including human movement and human respiratory activities such as breathing, coughing, and sneezing could be considered in deriving more comprehensive and realistic conclusions. More advanced ventilation studies should also be investigated to optimize the ventilation systems in healthcare facilities, thus minimizing the transmission of healthcare-acquired infection.

Declaration of Conflict of Interest

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

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