Transport of Contaminated Agents in Hospital Wards – Exposure Control with a Personalized Healthcare Ventilation System: Numerical Study

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ABSTRACT

Contaminated agents in hospital wards are the source of nosocomial infections known as hospital-acquired infection (HAI) or healthcare-associated infections (HAIs). Ventilation plays an essential role in the spreading and minimizing the transport of airborne infectious diseases such as Covid-19 and SARS in the hospital ward. The goal of this study is to explore elimination strategies for an efficient removal of contaminated agents, targeting the influence of using local air diffuser and exhaust. Computational Fluid Dynamics (CFD) technique was used to model the airflow field and contamination distribution in the ward environment. Simulated results showed that the bacteria spread from a patient confined to his bed was limited and under certain conditions significantly eliminated. Consequently, a relatively high efficiency of particle removal and a moderated transmission were obtained. Thus, this strategy is able to shorten the exposure time of patient and healthcare staff, as a result, mitigating cross-infection risk at the hospital.

Keywords: Ventilation system, Computational fluid dynamics, cross-infection risk

INTRODUCTION

There has been strong and sufficient evidence on the association between ventilation, air movements in buildings and the transmission/spread of infectious diseases (Li et al., 2007). Previous findings indicate that inhalation of airborne bacteria may constitute another dangerous exposure pathway.

The effect of heat sources on the airflow behaviour and contamination level was numerically investigated. The result shows that the presence of heat sources may modify temperature distributions and contamination level in different spots in a room in accordance to the distances and positions (Sadeghian, et al., 2021). According to a previous study of CFD predictions in the ward unit, air streams were generated by thermal buoyancy forces around a patient in the bed. The thermal plume generated from a person in the bed transports air from the surrounding into the breathing zone of the lying patient (Holmberg et al., 2009).

The main objective of this study is to analyse whether a proposed personal ventilation system, consisting of a local air diffuser and exhausts, is able to reduce the cross infection and provide acceptable comfort in a ward. Therefore, the temperature distribution and particle dispersion were prioritized in the study.

METHODS

The spread of diseases is closely associated to indoor air flow pattern created by room ventilation, which plays a significant role in minimizing the exposure of ward occupants to infectious agents. This work focuses on a numerical analysis of ventilation performance in order to monitor the transmission and removal of airborne infectious particles in a typical hospital ward using local air diffuser and exhaust.

A two-bed hospital ward unit has been considered in the present numerical simulations. The computational setup and related boundary conditions for CFD calculations have been taken from an actual ward unit. The information of the room geometry and the ventilation system were provided as follows.

Physical model

The two-bed hospital ward has a floor area of 5.4 m × 3.6 m, and 2.7 m in height. A general ventilation system is operated with 30 l/s and 20 °C in air diffusers under the two windows, and the air exhaust in the ceiling close to the opposite wall. The average room temperature is 21 °C. The schematic of the ward unit is presented in Figure 1.

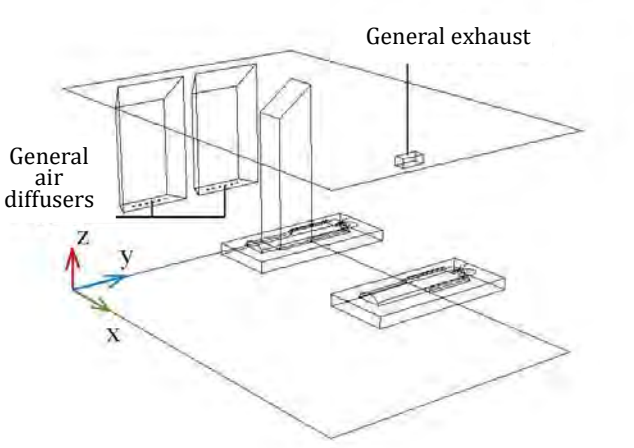

Figure1. Schematic of the ward unit used in this study with general ventilation

General ventilation consists of diffusers and a general exhaust. Two ventilation diffusers are located at the bottom of both windows. Fresh air with a temperature of 20 °C is supplied at a 45-degree angle towards the windows. The ventilation air is diffused at a rate of 15 l/s for each diffuser. The total inflow rate is thus 30 l/s. The exhaust area is 0.13 m × 0.28 m and located at the ceiling close to the door towards the hallway. In winter, the air supply is heated to warm up the room. The Air Change per Hour rate is 2.06 ACH.

To prevent infectious agents and other contaminants from moving in the direction towards the patient, or in the reverse direction out from a patient generating infectious droplets, local ventilation protection was arranged and tested in the CFD simulation in order to control particle movement. A local semi-sphere shaped air diffuser with a radius of 0.16 m was placed 0.5m above the head of the patient and forming a radial spread of fresh air. Two exhaust outlets below the breathing zone at both sides of the patient, functioning together with the local air diffuser, formed a push-and-pull air curtain protection around the patient as shown in Figure 2.

The balanced air flow rate for this personalized healthcare ventilation is 40 l/s with an inflow supplied at temperature of 19 °C. The configuration of the personalized healthcare ventilation system is illustrated in Figure2.

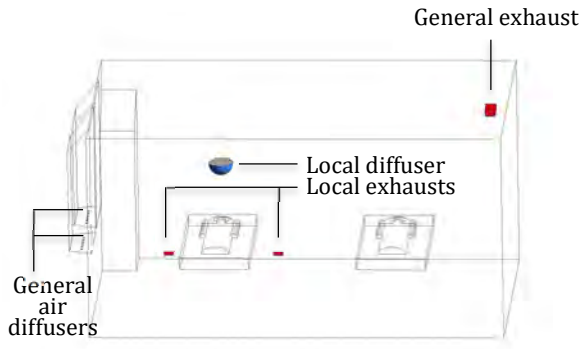

Figure 2. Outlines of the general ventilation and personalized healthcare ventilation system adopted in the ward room.

Numerical model

The CFD software ANSYS Fluent was used in the numerical simulation of the air flow in the room on a mesh using finite-volume method. The room is meshed with around 1.7 million cells. The airflow in the studied room is incompressible and turbulent. The standard k-ε turbulence model is used to deal with the turbulent effects. At solid wall surfaces, adiabatic conditions and wall functions were applied (FLUENT User's Guide). The SIMPLE algorithm is used for pressure- velocity coupling. The equation system is discretized in space with a second-order upwind scheme (FLUENT User's Guide). In the simulation, the ventilation airflow pattern, as well as inherent mixing properties and heat transfer, are explored. The air-flow patterns are computed with general ventilation, and additional local air diffuser and exhaust. Stably-lying patient models were taken in CFD calculations as heat sources. The heat flux to specify the thermal boundary conditions of the patient model in the present CFD is given in Table 1.

The size of the particles studied here is very small (2 μm to 20 μm) (Noble et al., 1963) with negligible influences on the air flow. Particle dispersion was thus predicted with one-way coupling using the particle tracking model available in ANSYS Fluent. The trajectories of discrete phase particles are predicted by integrating the force balance on the particles, which is formulated in a Lagrangian frame. Simulated particles sized 2 μm to 20 μm are released simultaneously from the sources close to the simulated patient's nose and mouth.

Table 1. Heat balance in bed with one person under the condition of ambient temperature at 20 °C

	Head	Torso, arms, and legs
Heat production (W/m^2)	140	54

RESULTS & DISCUSSION

The CFD simulation is to numerically analyse the exposure control with ventilation and the particle removal in the hospital ward. Ventilation and spatial parameters are mapped for a typical hospital ward. The temperature and contaminant particles are assessed as the main factors that may impose significant influence on the room air quality. Accompanying with the predicted airflow pattern, the pattern of airborne transmission is discussed below.

Flow features of the room ventilation in the hospital ward with no patient

As given by the CFD prediction, the general ventilation behaviour in the empty double-bed ward is illustrated in Figure 3a and Figure 3b. Figure 3a shows the airflow on a mid-section plane in parallel to x-axis with the velocity vectors colored by velocity magnitude (m/s). Figure 3b illustrates the contours of velocity magnitude (m/s) at 4 parallel planes, from left to right, (1) Ventilation diffusers from two windows toward the room, (2) Plane through the middle of the left patient bed, (3) Plane through the middle of the right patient bed, (4) Plane through the middle of the ventilation exhaust.

The ventilation system has the diffusers on the bottom of the window structure. The air diffused in the general ventilation moves upwards and exhausted through opening in the ceiling, as shown in Figure 3a. The velocity is relatively low in the middle of the room between two patient beds, as shown in Figure 3b. The mixing behaviour and low velocity of the air movement in the room may contribute to the inefficiency of airborne particle removal and leading to possible cross infection.

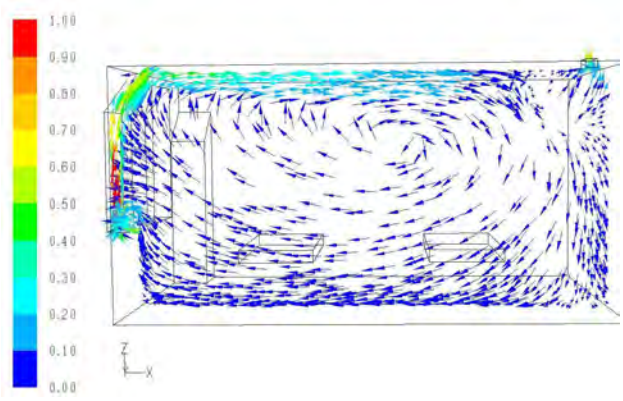

Figure 3a. General ventilation behaviour: velocity vectors in the empty double-bed ward.

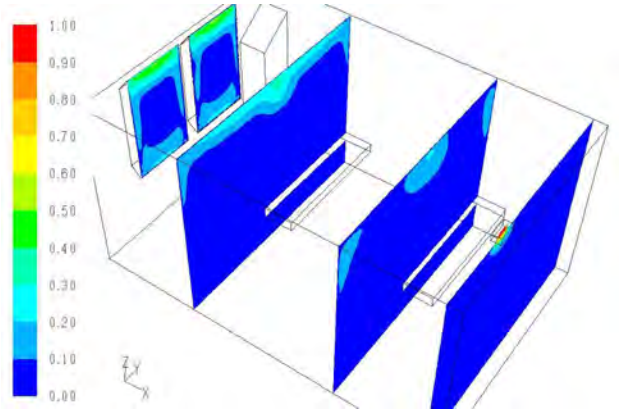

Figure 3b. General ventilation behaviour: contours of velocity magnitude (m/s) in the empty double-bed ward.

Flow features of the room ventilation in the hospital ward with 2 patients and with the aid of a personalized ventilation system

In the double-bed ward with room ventilation with 2 patients and supported further with a personalized ventilation system, the predicted velocity vectors colored by velocity magnitude (m/s) are shown in Figure 4a, and the contours of temperature (°C) are shown in Figure 4b. The low velocity (0.06m/s - 0.08 m/s) and the moderate temperature (19.5 °C - 20.5 °C) of the air curtain provide the patient with a comfortable environment. The presence of the patient, as a heat source, has created an uprising thermal plume, as shown in Figure 4a with the velocity field and in Figure 4b with the temperature contour.

Figure 5 illustrates the velocity vectors colored by velocity magnitude (m/s) in the double room. Also further demonstrated in this figure, is the upward air stream by thermal buoyancy from the right patient. Without the personalized ventilation system, the upward thermal plume by the right patient may transports the contaminants in the room. With the personalized ventilation system, an air curtain is formed over the left patient's breathing zone, which effectively prevents the spread of infectious contaminants.

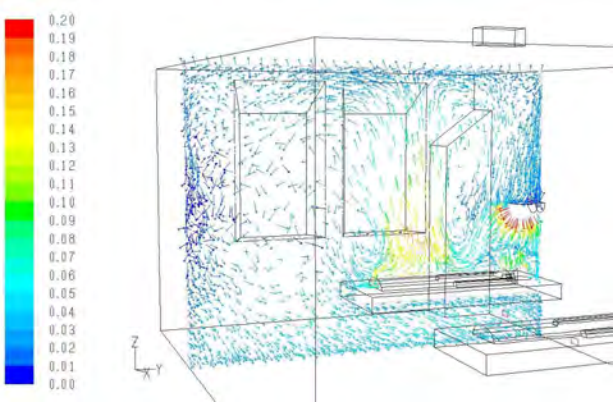

Figure 4a. The plane view of the predicted velocity vectors colored by velocity magnitude (m/s) through the middle of the left patient bed.

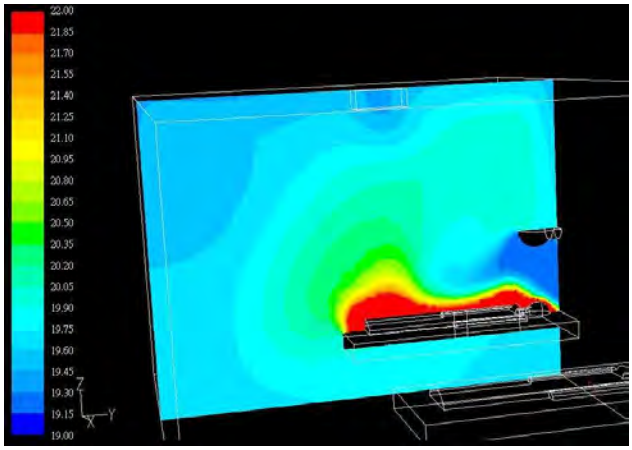

Figure 4b. The plane view of the predicted contours of temperature (°C) through the middle of the left patient bed.

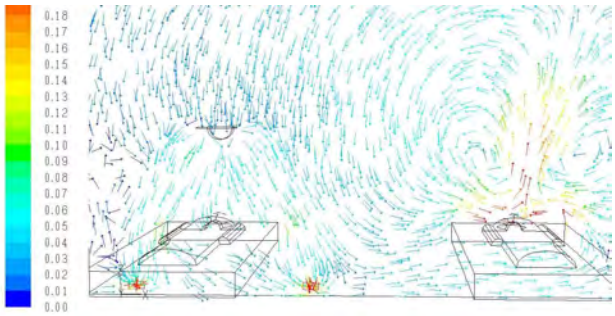

Figure 5. The predicted velocity vectors in the room colored by velocity magnitude (m/s).

Particle dispersion and removal

In the simulations of contaminant dispersion, particles with the size ranging from 2μm to 20μm were released in the patient breathing zone. In the original ward (with no local personalized ventilation system), particles were dispersed along with the air flow produced by room ventilation and influenced by the surrounding heat source, namely, the patient as heat source.

CFD predictions of the one-batch emission particle traces are shown in Figure 6. In the double-bed ward with one patient and the double-bed ward with two patients, ventilation started to remove particles after

50 minutes and 30 minutes, respectively, as disclosed in Figure 7a and Figure 7b.

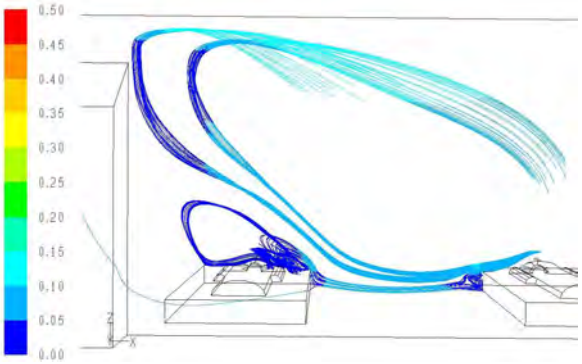

Figure 6. CFD predictions of the one-batch emission particle traces in the original patient room with only room ventilation. Particle traces colored by particle velocity magnitude (m/s).

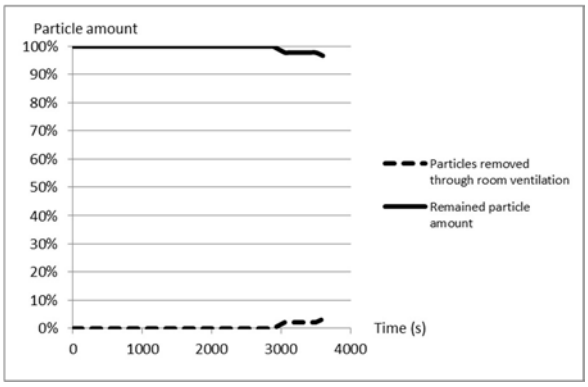

Figure 7a. Particle amount (%) in relation to time after one batch particles released in the double-bed ward with original room ventilation and one patient.

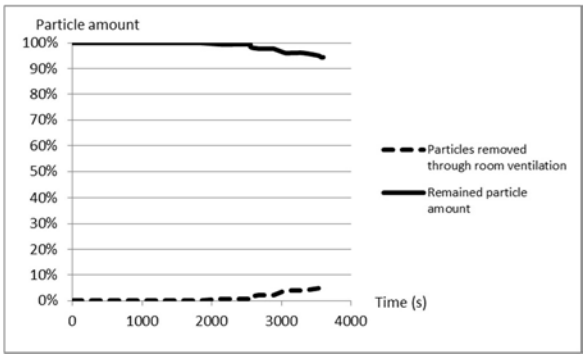

Figure 7b. Particle amount (%) in relation to time after one batch particles released in the double-bed ward with original room ventilation and two patients.

In the ward with a personalized ventilation system, the room airflow pattern is modified. The particles follow the plume generated by the thermal manikin above the head and torso. For the purpose of comparing the left-hand-side patient with personalized ventilation and the right-hand-side patient without, the personalized ventilation diffuser and exhausts are located only for the patient at the left. Figure 8a shows the path lines of the particles in the ward, colored by particle velocity magnitude (m/s), in the case that only the patient at the left releases particles. Figure 8b shows the path lines of the particles in the ward, colored by particle velocity magnitude (m/s), in the case that both patients release particles.

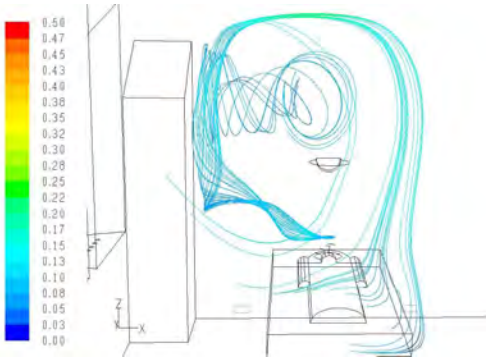

Figure 8a. The path lines of the particles in the ward colored by particle velocity magnitude (m/s) with only one patient (left) releasing particles.

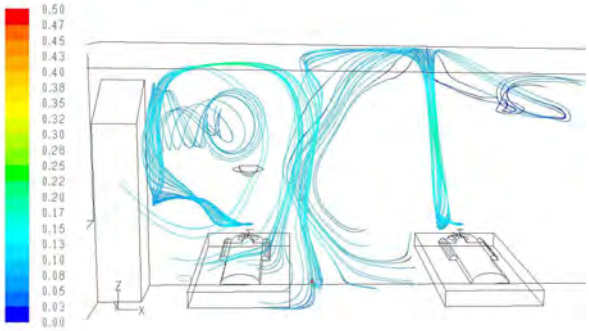

Figure 8b. The path lines of the particles in the ward colored by particle velocity magnitude (m/s) with both patients releasing particles.

The particle removal rate is shown in Figure 9. For the case when one batch of particles were released only from the left patient, 8% of the particles were removed solely through personalized ventilation after 1060 seconds (17 minutes and 40 seconds). In a time duration of 1500 seconds (25 minutes), the particles are removed through the personalized ventilation by 20% and, meanwhile, 9% is removed by room ventilation. 36% of particles were evacuated in 1800 seconds (30 minutes). More than half (53%) of particles were evacuated in 2700 seconds (45 minutes), 28% through personalized ventilation, and 25% through room ventilation. After that, 61% of particles were evacuated in 3300 seconds (55 minutes). Note that, after 3300 seconds (55 minutes), the remained particle amount in the room stayed stable for the rest of the first hour.

For the case when two patients are admitted in the ward and both release particles, as shown in Figure 8b above, the particles follow the upward plume from the patient at the right, inclining slightly towards the left. These particles subsequently move downward when they meet the airflow entailed by the left patient's plume and by the room ventilation diffusers. The path lines of the particles released by the patient at the right reach the torso part of the left patient,

however, the air curtain formed by the personalized ventilation prevents the transport routes into the left patient's breathing zone. The particle removal started after 150 seconds (2 minutes and 30 seconds) (Figure 10). In the duration of 240 seconds (4 minutes), particles were evacuated by 15%, and were removed solely through personalized ventilation. Room ventilation started the removal of particles after 255 seconds (4 minutes and 15 seconds) with relatively lower efficiency than personalized ventilation. In 360 seconds (6 minutes), 32% of particles were evacuated, In 920 seconds (15 minutes and 20 seconds), half (49%) of the particles were evacuated, 31% through personalized ventilation, and 18% through room ventilation. In 60 minutes, 79% of the particles were evacuated, 45% through the personalized ventilation and 34% through room ventilation. An interesting result was found when comparing the one-patient case in the double room and the two-patient case in the double room: the removed particles in the two-patient case were mainly released from the right patient, nevertheless, the air curtain formed by the personalized ventilation protects the left patient's breathing zone from the right patient's particle dispersion.

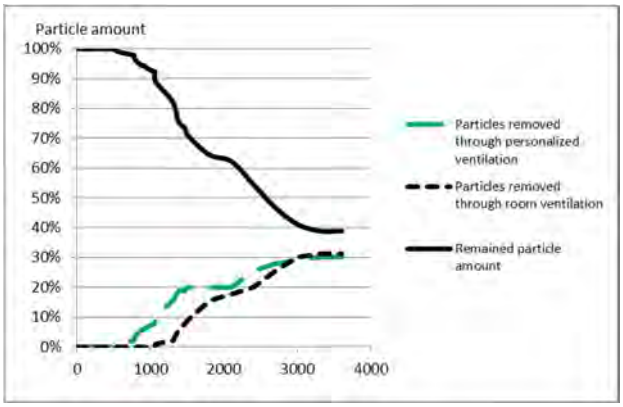

Figure 9. Particle amount (%) in relation to time after one batch of particles released only from the left patient in the ward with room ventilation and personalized ventilation system.

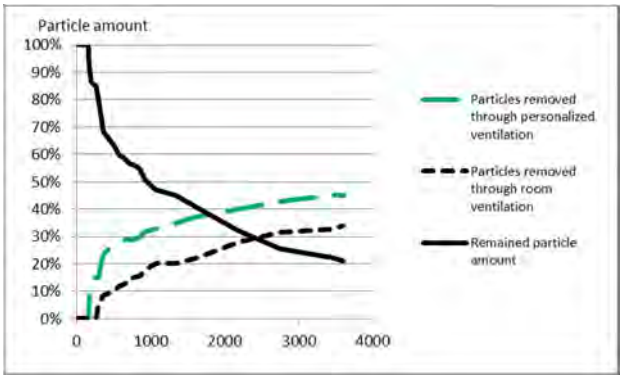

Figure 10. Particle amount (%) in relation to time after one batch of particles released from both patients in the ward with room ventilation and personalized ventilation system.

The amount of particles is reduced at a steady rate. With the installation of one personalized ventilation, the double room with two patients disposed of stray particles faster than the double room with only one patient.

As shown in Figure 11, the particle removal efficiency in the first hour increased from 3% to 61% in the case of one patient. In the case of two patients, the efficiency increased from 6% to 79%.

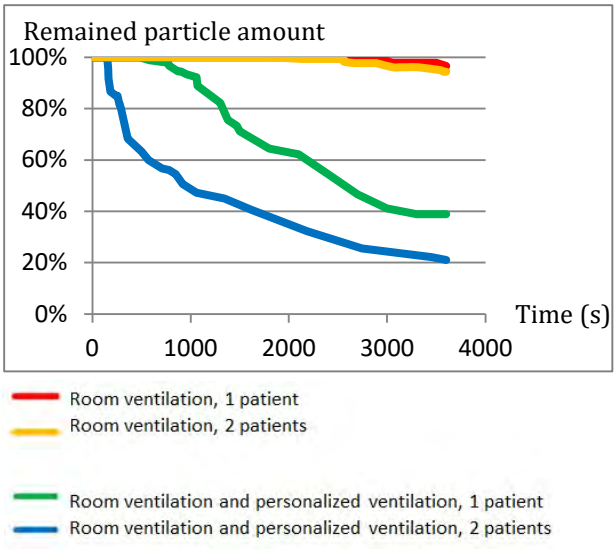

Figure 11. Remained particle amount (%) in relation to time after one batch of particles released in four settings.

The particle amount in the room was reduced by 61 % and 79 %, predicted after one hour in the double room with one patient and two patients, respectively, with the combination of room ventilation and the personalized ventilation (Table 2). Note that, each patient releases one batch of particles in the two-patient case, thus the particle counts are doubled of that in the one-patient case at time zero. However, after one hour, both cases only have slight difference in particle counts remained in the wards.

Table 2. Particle removal (%) in the first hour after one batch of particles released in four cases

	Particle removal in the first hour	Removed by room ventilation	Removed by personalized ventilation
Room ventilation, 1 patient	3%	3%	N/A
Room ventilation, 2 patients	6%	6%	N/A
Room ventilation and personalized ventilation, 1 patient	61%	31%	30%
Room ventilation and personalized ventilation, 2 patients	79%	34%	45%

CONCLUSIONS

This work explores the elimination technology for effective control and removal of infectious agents. The factors that influence the environment and contaminants concentration in hospitals, along with

infection control information, are considered in reference to previous studies. The process introduces CFD-based simulations and analysis to investigate the ventilation setup and performance, targeting to improve the indoor environment and air quality, and further to prevent cross infection for patients and hospital staffs in the wards. Numerical simulation (CFD) offers possibilities to follow the routes of airborne contaminants. This study demonstrates how a personalized local ventilation system may critically modify the room airflow pattern in association to the transmission of indoor bacteria-carrying particles in the air. Effects of ventilation parameters, including air flow rates and thermal conditions as well as the persons in the room are analyzed. The influence of local air diffuser and exhausts has been analysed and results from this part of the work are presented.

Particle spreading was modified in the presence of the local air diffuser, and the majority of particles were evacuated by the local exhausts with restricted interference to the neighbouring region. A bacteria spread from the one-patient case was limited and greatly eliminated: 53% removal in 2700 seconds (=45 minutes, equivalent to 3.6 times of air change) for the double-bed ward with one patient. For the double-bed ward with two patients, 49% removal in 920 seconds (about 15.3 minutes, equivalent to 1.23 air changes). With no local ventilation system, the general ventilation has ACH = 2.06. When combining with the personalized ventilation, ACH = 4.8, which contributes to the relatively high efficiency of particle removal, and further reducing the exposure time to the infectious agents for the patients and healthcare workers in the room.

The local personalized healthcare ventilation system is able to successfully prevent airborne infectious agents spreading between patients and surrounding persons in both directions. The results indicate that a combined local air diffuser and exhaust system is an effective solution to protect both the patient and persons in the ward room.

This research provides a valuable reference to minimize indoor contamination levels by using a personalized ventilation system. This local ventilation equipment could be a solution of hospital infection. Future work of this prototype will be conducted to optimize the ventilation system, for example, the heights and locations of the local diffuser(s) and the local exhausts or a movable equipment, to meet the need of providing fresh air and to enable efficient removal of infectious particles and bacteria in hospital and living environment.

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