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Numerical investigation on indoor environment decontamination after sneezing

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ABSTRACT

More than 320 million people worldwide were affected by SARS-CoV-2 or COVID-19, which already caused more than 5.5 million deaths. COVID-19 spreads through air when an infected person breathes, coughs, or sneezes out droplets containing virus. Emerging variants like Omicron with positivity rate of 16 (highest among others) present a greater risk of virus spread, so all types of indoor environments become critically important. Strategically adopted Heating Ventilation and Air Conditioning (HVAC) approach can significantly reduce the virus spread by early removal of contaminated aerosolized droplets. We modeled different HVAC configurations to characterize the diffusion of contaminated droplets cloud through Computational Fluid Dynamics (CFD) simulations of sneeze in standard hospital room as indoor scenario. Injection of saliva droplets with characteristics of exhaled air from lungs was applied to mimic real sneeze. CFD simulations have been performed for three HVAC configurations at two Air Change per Hour (ACH) rates; 6 and 15 ACH. For the first time, use of air curtain at low flow rate has been examined. Simulations provide high fidelity spatial and temporal droplets cloud diffusion under different HVAC configurations, showing spread in room indoor environment up to 360 s. Over 92% of ejected sneeze mass is removed from room air within seconds while the remaining 8% or less becomes airborne with droplets (<50 μm size) and tends to spread uniformly with regular HVAC configuration. Low-speed air curtain accelerates decontamination by efficiently removing aerosolized 1–50 μm size droplets. Study investigates role of droplets removal mechanisms such as escape, evaporation, and deposition on surfaces. Interestingly, results show presence of contaminated droplets even after 5 min of sneeze, which can be effectively removed using low-speed air curtain. Study finds that high ventilation rate requirements can be optimized to modify earlier and new hospital designs to reduce the spread of airborne disease.

1. Introduction

The novel human coronavirus, named Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) emerged in December 2019 and reached pandemic level (WHO, 2020). Despite restrictions, COVID-19 spread at a faster rate (Ong et al., 2020). A study based on 468 infection case reports from 93 cities in China found that people without symptoms transmit virus (Du et al., 2020). A study based on 468 infection case reports from 93 cities in China found that people without symptoms transmit virus (Du et al., 2020). A study based on 468 infection case reports from 93 cities in China found that people without symptoms transmit virus (Du et al., 2020). A study based on 468 infection case reports from 93 cities in China found that people without symptoms transmit virus (Du et al., 2020). A study based on 468 infection case reports from 93 cities in China found that people without symptoms transmit virus (Du et al., 2020). 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to gravity. On the other hand, smaller size droplets keep floating for a long time and may evaporate into aerosol or droplet nuclei; one of the main factors for long range transmission. Virus spread through aerosol and droplet nuclei is referred to as airborne transmission. According to (Wells, 1933), a 100 $\mu$m droplets would settle to the ground within 2 m of distance. However, droplets can travel distance of 6 m, the if sneeze jet velocity is 50 m/s (Xie et al., 2007). Studies have found that a respiratory turbulent cloud of buoyant gas is released with suspended droplets of variable sizes, which can travel up to 8 m before losing their momentum (Bourouiba, 2020). Though, the distance travelled by cloud depends on the wind speed (Obouk and Drikakis, 2020; Li et al., 2020).

Most of the studies in past and recent time employ quiescent environment for study. Droplet’s dispersion knowledge in a quiescent or wind conditions environment is valuable. However, it is of least

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**Fig. 1.** Designs of hospital room (a) Design 1, (b) Design 1 with Air Curtain, (c) Design 2, (d) Design 2 with Air Curtain, (e) Design 3 and (f) Design 3 with Air Curtain.
importance for indoor environments such as buildings, offices, and rooms. Indoor spaces are ventilated through pairs of diffuser and exhaust in the room. Experimental and numerical study by Zhou et al. (Zhou and Ji, 2021), shows that vortices generated in the room affect the transport of aerosols in the fever clinic room. Study finds spread of droplets is sensitive to the position of patient. Monitoring of pathogenic bioaerosols in a beef slaughter facility based on air sampling and airflow modeling finds that bioaerosols travel longer distance with the airflow streamlines. The objects available in path of airflow, modify the flow and get contaminated as aerosols impact on surfaces (Beck et al., 2019).

The potential risk of spread of infection through air was identified by WHO and is reason of concern specifically for indoor environment with large or small occupancies in presence of an infected person. Study by Ong et al. in a room with three COVID patients founds that 87% of room samples, 60% of toilet sites, one swab of a shoe tested positive (Rapid Expert Consult. Possibility Bioaerosol Spread SARS-CoV-2 COVID-19 Pandemic (April 1, 2020), 2020). A swab collected from the air exhaust also tested positive suggesting that viral droplets were carried by air and deposited on the vents (Ong et al., 2020). Systematic sampling and analysis of SARS-CoV-2 RNA in different hospital areas to assess viral spread show greater risk of nosocomial infection, even without direct exposure to the exhaled breath of infected patients. Study suggests evaluation of ventilation system to minimize risk (Grimalt et al., 2022).

In the case of respiratory diseases, it is recommended to have air exchange rate $\geq 15$ ACH, along with maximum use of outdoor air and disabled recirculation. Studies also consider change in position of ventilation ducts to offer maximum comfort and effective removal of contaminated air from surroundings (Megahed and Ghoneim, 2021). Appropriate knowledge of air flow patterns and ventilation rate in presence of stationary objects in the room can help realize the goal of effective decontamination from virus loaded micron sneeze droplets.

The study presented in this paper focuses on the role of air flow patterns due to different HVAC configurations on removal of contaminated micron size droplets from indoor environment of a hospital room.

**Table 1**

| Design name | Location of diffuser from bed | Location of exhaust from bed | Figure number |
|-------------|--------------------------------|-------------------------------|---------------|
| Design 1 (D1) | Left                          | Right                         | 1a            |
| Design 1 with Air Curtain (D1_AC) | Left                          | Right                         | 1b            |
| Design 2 (D2) | Right                         | Left                          | 1c            |
| Design 2 with Air Curtain (D2_AC) | Right                         | Left                          | 1d            |
| Design 3 (D3) | Left                          | Right Below                  | 1e            |
| Design 3 with Air Curtain (D3_AC) | Left                          | Right Below                  | 1f            |

**Table 2**

Dimensions of scaled NIH prototype hospital room.

| Parameter | Hospital room | Scaled room | Scaling ratio |
|-----------|---------------|-------------|---------------|
| Room length, width, height (m) | 5.146, 2.706, 2.746 | 3.86, 2.03, 2.06 | 0.75 |
| Air diffuser opening face area ($m^2$) | 0.3716 | 0.2090 | 0.5625 |
| Air exhaust opening face area ($m^2$) | 0.3716 | 0.2090 | 0.5625 |
| Air curtain length, width (m) | 0.6906, 0.077 | 0.4572, 0.0575 | 0.75 |
| Patient mouth opening area ($m^2$) | 0.00263 | 0.00148 | 0.5625 |

**Table 3**

Dimensions of scaled diffuser.

| Parameter | Diffuser dimensions (cm) | Scaled diffuser dimensions (cm) | Scaling ratio |
|-----------|--------------------------|-------------------------------|---------------|
| Inlet neck diameter | 25.4 | 19.05 | 0.75 |
| 1st cone top ring, bottom ring | 54.19, 38.92 | 40.64, 29.19 | 0.75 |
| 2nd cone top ring, bottom ring | 38.72, 18.10 | 29.04, 13.5714 | 0.75 |
| 3rd cone top ring, bottom ring | 24.39, 8.04 | 18.29, 6.0275 | 0.75 |
| 4th cone top ring, bottom ring | 14.49, 6.41 | 10.87, 4.81 | 0.75 |
| Cone plates inclination angle | 45° | 45° | 1 |

Fig. 2. (a) top view, (b) side view, (c) geometrical solid surface side view and (d) isometric cut view of the air inlet diffuser.
after a sneeze event by an infected patient. The effectiveness of ventilation rates 6 ACH against 15 ACH has been compared in all HVAC configurations. Study aims to discover the options of using low flow ventilation rates for an efficient decontamination, so that hospitals with 6 ACH could also be converted in COVID-19 rooms/hospitals to accommodate extensive hospitalization. Thus, additional use of air curtain has been proposed and examined in this study. Compared to traditional high flow rate air curtains used in malls, offices, facilities, buildings etc., the study investigates use of low flow rate air curtains. The goal is that hospitals should be able to employ low flow rate-based air curtains or ducts with minor modifications in air distribution system and expedite the decontamination of indoor environment. CFD modeling using Eulerian-Lagrangian method has been implemented to simulate the sneeze in a ventilated indoor environment of hospital room. The location of diffuser and exhaust plays critical role in generating the airflow patterns leading to the spread of droplets. Effect of air flow patterns on droplets removal processes such as escape through exhaust, evaporation into vapor phase and deposition on the surfaces has been examined. Study includes evaluation of HVAC configurations and ventilation rate on effective removal of droplets of different size groups. The overall airborne droplets removal percentage has been compared for different HVAC configurations. Based on the study, recommendations for efficient HVAC configuration for effective decontamination has been presented.

2. Methods

Sneeze is a mechanism of respiratory system to avoid any stimulus getting into the upper respiratory tract. Pressure induced by spasmodic contraction of the internal intercostal and abdominal muscles works as driving force for sneeze. Large pressure variation in a short time interval

| Zone                      | Boundary condition                  | Temperature | Velocity |
|---------------------------|-------------------------------------|-------------|----------|
| Patient                   | Constant Temperature (38°C)         |             | No slip  |
| Room walls, floor, and    | Adiabatic                            |             | No slip  |
| roof                      |                                      |             |          |
| Chair and monitor         | Adiabatic                            |             | No slip  |
| surface                   |                                      |             |          |

Table 4 Details of boundary conditions.

| Design                     | Number of cells | Design | Number of cells |
|---------------------------|-----------------|--------|-----------------|
| Design 1 (D1)             | 484,022         | Design 1 with Air Curtain (D1_AC) | 520,419 |
| Design 2 (D2)             | 485,848         | Design 2 with Air Curtain (D2_AC) | 521,433 |
| Design 3 (D3)             | 483,876         | Design 3 with Air Curtain (D3_AC) | 519,766 |

Table 5 Number of cells used for CFD simulations in different hospital room designs.

Fig. 3. Hospital room top view of (a) D1, (b) inner meshed view of walls of rooms without air curtain (c) meshed view in a plane passing over the patient body, and (d) zoomed meshed view of the upper left corner of the room.
creates a fast flow in the upper respiratory tract, which breaks the saliva and mucus into small size droplets from mouth cavity, which ultimately gets sprayed in the atmosphere. The sneeze ejecta is treated as a mixture of aerosols and droplets in transient manner. Studies have found that pressure response is the key time varying parameter to understand the spray of micron size droplets (Gupta et al., 2009). However, the transient pressure response of sneeze varies for individuals, leading to different size distribution of exhaled droplets (Han et al., 2013b). The study presented in this paper simulates a sneeze from a patient lying on an inclined bed at 15° in a hospital room. Geometrical design has been discussed in the following section.

2.1. Geometrical design of hospital room

Multiple hospital room design with different configurations of diffuser and exhaust location has been adopted worldwide. According to National institute of Health (NIH) guidelines, a scaled hospital room of volume 16.142 m$^3$ (L × W × H = 3.86 m × 2.03 m × 2.06 m) with a diffuser, exhaust, patient bed, chair, and the monitor has been considered to study the sneeze droplets. Dispersion under influence of air flow patterns. Three widely adopted basic hospital room designs along with proposed modified designs (using air curtain) have been shown in Fig. 1. The air curtain was installed to prevent pathogens from entering the room. The room designs considered for the present study have been summarized in Table 1.

Generally, hospital rooms are ventilated at 6 ACH following ASHRAE guidelines. However, in the case of respiratory disease, the hospital rooms are ventilated at 12 ACH or higher. The location of diffuser and exhaust plays critical role in development of air flow patterns leading to transport of contaminated droplets in indoor environment. The scaling ratio of all the objects present in the room has been shown in Table 2. The necessary coordinate details of the hospital room, diffuser, exhaust, and air curtain have been presented in supplementary information section S1.

2.2. Geometrical design of diffuser

The air inlet diffuser shape, number of cones/blades, and angle of cones play critical role in development air flow patterns and hence dispersion of droplets in indoor environments of room. This paper simulates standard 4-way diffuser (Fig. 2a -2d) that guides inlet air in four directions with the help of integrated three cones arranged at a 45° angle. The diffuser dimensions are shown in Table 3.

3. Numerical method

The sneeze can be simulated using two-way Eulerian-Lagrangian approach. Thus, dynamics of a single droplet coming from the sneeze acts on a sub-grid scale and interacts only with the resolved Eulerian macro-scales by exchanging mass, momentum, and energy. The air has been simulated as continuous phase and sneeze droplets as discrete phase. The CFD simulations has been performed using ANSYS FLUENT 2019R3 (“ANSYS Fluent User Guide,” n. d.).

3.1. Eulerian model

The continuous phase (air) has been modeled as compressible homogeneous mixture of dry air and water vapor by solving the conservation equations for scalar variables that represent the mass fraction $Y$ of each species in the mixture. The mixture properties were calculated as the mass fraction of the mixture species component. Mixture property $\phi_{\text{mix}}$ is calculated using component property values

$$\phi_{\text{mix}} = Y_a \phi_a + Y_v \phi_v$$

where, $Y_a$, $Y_v$, and $\phi_a$, $\phi_v$ are the mass fractions and property values of air and water vapor respectively. It was assumed that air and water vapor make homogeneous mixture and share same local velocity, pressure, and temperature. The Eulerian and Lagrangian phase interaction was...
achieved by interphase mass, momentum, and energy exchange. The Reynolds number based on equivalent hydraulic diameter $D_h = 4 \cdot A/P_w$ of the mouth opening, and peak velocity is 20,000. Here $A$ is mouth opening area, $P_w$ is mouth opening perimeter. The turbulence Reynolds Averaged Navier-Stokes (RANS) realizable k-epsilon model with scalable wall function was implemented to close the turbulence problem. The model equations can be found in ANSYS Fluent V2019R3 theory guide (“Fluent Theory Guide,” n. d.).

3.2. Lagrangian model for droplets

The sneeze droplets tracking is critical for understanding droplets dispersion in room. Details of available discrete phase models are available in the user guide (Fluent Inc, 2016). Models for tracking and mass balance have been discussed in the following sections—

3.2.1. Droplet tracking model

The discrete phase is solved using Lagrangian method by integrating the force balance on the particle. The force balance on the droplet equates the particle inertia with the forces acting on the particle. This can be written in cartesian form as

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g(\rho_p - \rho)}{\rho_p} + F_x.$$

where, $F_D(u - u_p)$ is the drag force per unit particle mass and $F_x$ is an additional acceleration (force/unit particle mass) term.

$$F_D = \frac{18\mu}{\rho_p d_p^2} C_D Re \quad (3)$$

Here, $u$ is fluid phase velocity, $u_p$ is particle velocity, $\mu$ is viscosity of air.
the fluid, $\rho$ is fluid density, $\rho_p$ is density of the particle, $d_p$ is particle diameter and $C_D$ is drag coefficient. The relative Reynolds number $Re$ is defined as

$$Re = \frac{\rho d_p |u_p - u|}{\mu}$$

(4)

In present studies, the Saffman lift force has been included (Saffman, 2018). The lift force used is from Li and Ahmadi and is a generalization of expression provided by Saffman:

$$\vec{F} = \frac{2K\nu \rho d_p}{\rho_p d_p (d_p d_p)} \left( \vec{v} - \vec{v}_p \right)$$

(5)

where $K = 2.594$ and $d_{ij}$ is the deformation tensor. This form of lift force is intended for small particle Reynolds number. Discrete Random Walk Model and Random Eddy Lifetime was used to perform stochastic tracking of the droplets. The relevant equations can be found in Fluent theory guide (“Fluent Theory Guide,” n. d.).

3.2.2. Droplet evaporation model

The droplets evaporation is mainly governed by the diffusive flux of the droplet vapor in the air,

$$N_v = k_c (C_{vd} - C_{va})$$

(6)

Here, $N_v$ is molar evaporative flux of vapor, $k_c$ is mass transfer coefficient, $C_{vd}$ is concentration of vapor at saturated pressure $P_{sat}$ on the droplet surface. The saturated pressure of water is lowered by non-volatile components such as mineral salts which affects the evaporation rate of the droplet. The activity coefficient of water is defined as ratio of saturated vapor pressure of pure water and water containing

Fig. 7. Air velocity streamlines for rooms with design (a1) D1, (b1) D1_AC, (a2) D2, (b2) D2_AC, (a3) D3, and (b3) D3_AC at 15 ACH.
salt. Therefore, the $C_{vd}$ is related to saturated vapor pressure and $C_{va}$ is related to partial vapor pressure given by

$$C_{vd} = \frac{P_{sat} R T_d}{d},$$

and

$$C_{va} = \rho v P R T_a$$

Here $T_d$ is droplet surface temperature. $\rho v$ is species fraction, $P$ and $T_a$ are the local pressure and temperature respectively. The mass transfer coefficient $k_c$ is calculated in correlation with Reynolds and Schmidt number using following equation:

$$k_c = \frac{D_{dv}}{D_d} \left( 2.0 + 0.6R^{0.3}Sc^{1/3} \right)$$

Here, $D_{dv}$ is known as diffusion coefficient of vapor in the air with the following droplet mass evolution equation:

$$m_d(t + \Delta t) = m_d(t) - N A_d M_d \Delta t$$

where $m_d$ is droplet mass, $M_d$ is molecular weight, and $A_d$ is surface area. The droplet temperature governed by thermal balance including latent and sensible heat is estimated by following equation:

$$m_d C_{pd} \frac{dT_d}{dt} = h A_d (T_a - T_d) - \frac{dm_d}{dt} h_f g$$

where $h_f g$ is known as latent heat of droplet, $h$ is heat coefficient, which is calculated using modified Nusselt number:

$$h = \frac{\lambda ln(1 + B_T)}{D_d B_T} \left( 2.0 + 0.6R^{0.3}Pr^{1/3} \right)$$

where $\lambda$ is thermal conductivity of air, $B_T$ is Spalding heat transfer number.

$$B_T = \frac{C_{pu}(T_u - T_d)}{h_f g \left( \frac{1}{T_u} - \frac{1}{T_d} \right)}$$

where $m_u$ is droplet evaporation rate and $q_d$ is the heat energy trans-
ferred to the droplet.

The droplets' distortion and breakup was accounted using Taylor Analogy Breakup (TAB) model (O'Rourke and Amsden, 1987). Taylor analogy considers distorting droplet as a damped spring-mass system. It accounts only for fundamental oscillation mode of droplet. The TAB considers droplet shape oscillation, distortion, and breakup. The details of the Taylor analogy can be found in fluent theory guide (“Fluent Theory Guide,” n. d.).

3.4. Boundary conditions

For CFD simulations, the vertical walls, floor, roof, monitor surface, hospital bed, chair and air deflecting cones of the air inlet diffuser were considered adiabatic. No slip boundary condition was imposed on all the surfaces. The temperature and velocity boundary conditions are shown in Table 4.

Fig. 9. Distribution of droplets at 6 ACH for (a1) D1, (b1) D2, (c1) D3, (a2) D1_AC, (b2) D2_AC, (c2) D3_AC and at 15 ACH for (d1) D1, (e1) D2, (f1) D3, (d2) D1_AC, (e2) D2_AC, (f2) D3_AC at t = 10 s.
4. Setup and initial boundary conditions

The dimensions of different hospital room designs considered for simulation has been shown in Fig. 1. The domain meshing was performed using ANSYS by adopting polyhedral unstructured scheme (Fig. 3). Meshed top view of design D1, is shown in Fig. 3a. Fig. 3b shows an inner meshed view of walls of rooms without air curtain, while Fig. 3c shows meshing in the plane passing over the patient body and in the breathing zone. Refined meshes near the wall (shown in red square in Fig. 3c) have been shown in Fig. 3d. The meshing approach was repeated for all the geometries shown in Fig. 1. A grid independence study was performed for different hospital room designs shown in Fig. 1 at 15 ACH ventilation rate. Details of the grid independency study have been discussed in supplementary information section S2. Based on grid independency, the following number of cells shown in Table 5 were used for further simulations.

Fig. 10. Distribution of droplets at 6 ACH for (a1) D1, (b1) D2, (c1) D3, (a2) D1_AC, (b2) D2_AC, (c2) D3_AC and at 15 ACH for (d1) D1, (e1) D2, (f1) D3, (d2) D1_AC, (e2) D2_AC, (f2) D3_AC at t = 20 s.
For the simulations, pressure-velocity coupling was performed using the SIMPLE approach. The pressure was discretized using second order; density, momentum, turbulent kinetic energy, turbulent dissipation rate, and energy were discretized using a second-order upwind scheme. To begin, initially steady state simulations are performed to obtain a converged solution for air flow and heat transfer including concentration of species for air and vapor. Steady state results were used as an input to perform transient simulations. The transient simulations were performed for 600 s and 240 s to achieve one complete air exchange at 6 ACH and 15 ACH ventilation rate respectively before injecting sneeze droplets in the room. The indoor air velocity of the hospital room was considered a critical parameter to predict the droplets spreading. The convergence limit for continuity, velocity, k, epsilon, and water vapor was set to $10^{-5}$ and for energy $10^{-8}$. The droplets tracking accuracy was set to $10^{-5}$.

In present study, the sneeze droplets originate from a mouth opening.

Fig. 11. Distribution of droplets at 6 ACH for (a1) D1, (b1) D2, (c1) D3, (a2) D1_AC, (b2) D2_AC, (c2) D3_AC and at 15 ACH for (d1) D1, (e1) D2, (f1) D3, (d2) D1_AC, (e2) D2_AC, (f2) D3_AC at $t = 40$ s.
area of 2.25 cm². The single sneeze droplets diameter vary from 1 μm–1000 μm based on the experimental study performed by Han et al. (2013b). It follows the average number size distribution based on the quantity proportion averaged per person. In the simulations, rosin-rammler diameter distribution (“Fluent Theory Guide,” n. d.) method was used with a mean diameter of 90 μm and spreading parameter of 1.99. The generation of sneeze is characterized by mixture of relatively hot humid air from lungs and water droplets. The droplets were injected in +yz direction (towards the feet of patient) for a period of 0.2381 s with cumulative mass of 6.3 mg. The coordinate axis is shown in Fig. 1. Each sneeze droplet is assumed to constitute of 93.5% of water and 6.5% of salt in terms of mass fraction. Experimentally, it is found that cough and sneeze show similar pressure response (Gupta et al., 2009).

Following the pressure profile, a transient sneeze velocity shown in Fig. 4 was implemented in simulations. The sneeze droplets have same velocity as the turbulent cloud when expelled from mouth. The velocity profile for both humid expiratory air and sneeze droplets can be

Fig. 12. Distribution of droplets at 6 ACH for (a1) D1, (b1) D2, (c1) D3, (a2) D1_AC, (b2) D2_AC, (c2) D3_AC and at 15 ACH for (d1) D1, (e1) D2, (f1) D3, (d2) D1_AC, (e2) D2_AC, (f2) D3_AC at t = 60 s.
obtained from the following function:

\[ v(t) = a_1 \left( \frac{t}{c_1} \right)^{b_1} e^{-\frac{t}{c_1}}, \quad \frac{d}{c_1} \left( \frac{t}{c_2} \right)^{b_2} e^{-\frac{t}{c_2}} \text{ m/s} \]

where the value of coefficients are.

\[ a_1 = 12.7124, \quad a_2 = -36.8307, \quad b_1 = 5.7364, \quad b_2 = 4.9688, \quad c_1 = 0.0360, \quad c_2 = 0.0373, \quad \text{and} \quad d = 0.0244. \]

The droplets start coming out of the mouth cavity along with the sneeze air since beginning of the expiratory event. The droplet injection stops in 0.2381 s, while the remaining air in the lungs is exhaled up to 0.55 s (Fig. 4) (Busco et al., 2020). Sneeze droplets and humid air from mouth cavity are assumed to have initial temperature of 38 °C. The droplet tracking accuracy control tolerance is set to 1e-5. The transient jet velocity profile is implemented as a User Defined Function (UDF) based on ANSYS Fluent Theory, platform.

For the simulations, the temperature and relative humidity of inlet supply air was set to 25 °C (298.15 K) and 50% respectively. The inlet air velocity corresponding to 6 ACH and 15 ACH is set to 0.95 m/s, and 2.4 m/s respectively. The air inlet velocity from air curtain is set to 0.90 m/s. All the simulations were performed for a period of 360 s.

5. Results and discussion

The hospital rooms are ventilated through a central HVAC system. The cold inlet air is distributed by diffuser, which interacts with surfaces leading to development of a flow pattern. After ejection, large size sneeze droplets quickly fall on the ground while medium and small size droplets may become airborne by losing significant mass. Therefore, study presented in this paper discusses both air flow and droplets dispersion in rooms of different design in following sections.

3.3. Model assumptions

Following assumptions were made to simulate the sneeze droplets dispersion in the indoor environment of room-

1. Diffuser distributes the inlet air equally in all direction with help of cones.
2. The exhaust egg crate grid walls are thin enough to be neglected. Therefore, exhaust is a square outlet duct.
3. The hospital door is considered close throughout the simulation in all the cases.
4. Air curtain was considered delivering air at same temperature and relative humidity like main diffuser.
5. The patient body was considered to have 311.15 K (38 °C) temperature.
6. Heat transfer due to radiation was neglected.

5.1. Validation of the evaporation model

An exhaustive priori droplet evaporation model validation was
performed before CFD case studies. The droplets evaporation model was validated with the experimental data in literature. Ranz-Marshall experimentally investigated the evaporation of motionless droplet of 1050 μm in a dry environment with 0% relative humidity (RANZ, W.E., Marshall, 1952). Droplet and surrounding initial temperature were 9 °C and 25 °C respectively. Fig. 5 a shows that CFD results agree well with the experimental finding beyond 360 s duration. In addition, the CFD evaporation model was also validated for free fall of droplet in a humid environment. The experimental data form Hamey and Spillman was used to validate the model (Hamey, 1982; Spillman, 1984). Hamey investigated evaporation rate of droplets of diameter 115 μm, 110 μm at 16 °C falling in humid environment of 20 °C and 70% relative humidity. Similarly, Spillman investigated the evaporation rate of droplet of diameter 170 μm at 25 °C in a humid environment at 31 °C and 68% relative humidity. The CFD model show a good agreement with the literature data (Fig. 5 b). The details of experimental conditions are also reported within the figures.

5.2. Air flow streamlines development in the room

The fresh inlet air from HVAC supply system gets distributed by diffuser. The air velocity keeps decreasing away from diffuser. In the presence of stationary objects, the location of diffuser and exhaust play a critical role in development of air flow patterns, which determine the dispersion path of contaminated sneeze droplets. The air flow patterns in all six designs (Table 1) with two ventilation rates 6 ACH and 15 ACH are shown in Fig. 6 and Fig. 7 respectively.

At 6 ACH ventilation rate, Fig. 6a1 show that air streamlines travelling towards the left lead the overall flow development forming a loop in the form of eight. Air streamlines directed towards exhaust leave the domain except few due to deviate from its path. Fig. 6b1 for design D1_AC show that streamlines from air curtain pass below the bed, push the air towards right of the room and deflect towards exhaust. Fig. 6a2 for design D2 show that right part of the room has turbulent zone. The streamlines travel below the bed, gets reflected from left wall and return towards the exhaust. Fig. 6b2 for design D2_AC show that air curtain reorganizes the flow streamlines. The diffuser air travelling towards the left wall is not strong enough to oppose the flow from air curtain. The air curtain air flows below the bed, interacts with air from diffuser and move towards the exhaust. Fig. 6b3 for design D3 show that air curtain air flows concurrently. As a result, relatively large number of streamlines terminate at exhaust.

At 15 ACH ventilation rate, local air velocity remains high compared to 6 ACH. The room design D1 exhibit similar air flow pattern for both 6 ACH and 15 ACH (Fig. 6a1 and 7a1). Thereby forming large vortex in left part of the room. Fig. 7b1, for design D1_AC show that air from air curtain supports the overall flow of diffuser air from left part of the room. A substantial part of air from air curtain passes blow bed and breaks the vortex on the right part of room. Fig. 7a2, for design D2, shows flow patterns like 6 ACH by forming large vortices in both left and right part of the room. Fig. 7b2, for design D2_AC show that air curtain air
interacts with air from right part of the room and form vortex in left part of the room. Fig. 7a3, for design D3 shows flow pattern like 6ACH ventilation rate (Fig. 6a1). The diffuser air reflected from right wall of the room return towards exhaust and leave the room. Fig. 7b3 for design D3_AC shows effect of air curtain. The diffuser air after reflection from left wall gets mixed with air from air curtain and travel towards the ceiling. Streamlines forms large circulating vortex in the right part of the room and leave the room through exhaust.

Additionally, at both the ventilation rates (6 ACH and 15 ACH), the Coanda effect was seen for the design D1, D2, D1_AC and D2_AC. Under the Coanda effect, the airflow clings to the ceiling. As the airflow moves along the ceiling, its movement is extended along that surface and projected farther into the room. The effect could be minimized by placing the exhaust near the floor, and typically behind the patient.

5.3. Droplets distribution in a room

During respiratory event like sneeze the mucus breaks into large number of micron size droplets and released in the air. Large droplets carry momentum and travel longer distances, while the smaller size droplets travel a shorter distance, get deviated from the path and start spreading in the form of a cloud. It must be noted that sneeze droplets interact with the surrounding air and get influenced by the flow pattern developed in the room. Since ejection, all the droplets are subjected to evaporation, deposition, and escape through exhaust. High temperature difference between droplets (38°C) and surrounding air (25°C) causes rapid evaporation. The rate of evaporation decreases during thermalization process. The gradual loss of mass results in decreases of size tending to suspend the droplet in air instead of depositing on surfaces. In the deposition process, droplets deposit on the walls and solid surfaces. While in the process of escape, the droplets leave the room through exhaust. As a combination of all three processes, the sneeze mass injected in the room decreases with time.

The dispersion of sneeze droplets in indoor environment of room with design D3 at different time instants have been shown in Fig. 8. A comparison of Figs. 8 and 7a3 show that sneeze droplets follow air streamlines. The Fig. 8a shows ejection of droplets, Fig. 8b shows large size droplets falling towards the ground, Fig. 8c shows droplets spreading towards the right wall of the room, Fig. 8d shows small size droplets following the air flow (moving downwards), Fig. 8e shows development of high droplets number concentration zone and Fig. 8f shows almost uniform distribution of droplets in the room at 60 s. Also, Fig. 8a–d shows that most of the large size droplets (>100 μm) deposit over the patient bed and in surrounding area. Transient spread of sneeze droplets in room ventilated at 6 ACH and 15 ACH time has been shown in the Fig. 9 (at 10 s), Fig. 10 (at 20 s), Fig. 11 (at 40 s), and Fig. 12 (at 60 s).

Fig. 9 shows dispersion of droplets in rooms of different configuration at 6 ACH and 15 ACH. Fig. 9a1, 9b1 and 9c1 show that droplets move away from the diffuser towards exhaust following the streamlines for design D1, D2 and D3 respectively at 6 ACH ventilation rate. Fig. 9c1 show that droplets move towards the right front corner following the flow circulation zone developed in the corner (Fig. 6a3). Effect of air curtain on droplets dispersion can be seen from Fig. 9a2, 9b2 and 9c2 for...
design D1_AC, D2_AC and D3_AC respectively at 6 ACH ventilation rate. As can be seen from Fig. 6b1, 6b2 and 6b3 that most of the air passes below patient bed, which results in local air circulation zones development in the left and right part of the room. Compared to other, the effect of air curtain is more apparent for room with design D3. Air curtain accelerates the spread of droplets as can be seen by comparing Fig. 9c1 and 9c2. Similarly, Fig. 9d1, 9e1 and 9f1 show that droplets move away from the diffuser towards exhaust following the streamlines (Fig. 7a1, 7a2 and 7a3) for design D1, D2 and D3 respectively at 15 ACH ventilation rate.

The magnitude of dispersion is found to be higher compared to 6 ACH ventilation rate. In rooms D1 and D3 droplets reach the right wall and fill up the upper right corner of the room, while in design D2 particle shift towards left of room. Fig. 9d2, 9e2 and 9f2 show dispersion of droplets for the rooms with design D1_AC, D2_AC and D3_AC respectively at 15 ACH ventilation rate. Modified streamlines due to air curtain (Fig. 7b1, 7b2 and 7b3) restrict the spread of droplets.

Fig. 10 shows dispersion of droplets in room of all design (Table 1) at 6 ACH and 15 ACH at 20 s. Fig. 10a1, 10b1 and 10c1 shows spread of droplets in room with design D1, D2 and D3 at ventilation rate of 6 ACH. Droplets start approaching the floor and breathing height in each room. The droplets in room D3 at 6 ACH found spreading diagonally (Fig. 10c1). Effect of air curtain on droplets dispersion can be seen from Fig. 10a2, 10b2 and 10c2 for design D1_AC, D2_AC and D3_AC respectively at 6 ACH ventilation rate. Fig. 10a2 and 10b2 show that air from air curtain limit the spread of droplets near the entrance (left wall). Droplets spread pattern (Fig. 10c2) can be seen in room D3_AC under the influence of air curtain. Dispersion of droplets in rooms with design D1, D2 and D3 at 15 ACH has been shown in Fig. 10d1, 10e1 and 10f1. Strong air flow from diffuser forces the droplets to accumulate near the walls on opposite sides and near the remote corners. The droplets are found to be covering a larger volume of the room on right (for D1), on left (for D2) and on right (for D3). Effect of air curtain in all three rooms with design D1_AC, D2_AC and D3_AC at 15 ACH ventilation rate has been shown in the Fig. 10d2, 10e2 and 10f2 respectively. In the background of streamlines developed in room (see Fig. 7b1, 7b2 and 7b3), air from air curtain passes below the patient bed and control the spread of cloud. Additionally, air curtain keeps the rooms cleaner compared to room without air curtain.

Fig. 11 shows dispersion of droplets in rooms of different designs (Table 1) at 6 ACH and 15 ACH at 40 s. Fig. 11a1, 11b1 and 11c1 shows spread of droplets in room with design D1, D2 and D3 at ventilation rate of 6 ACH. Among all three rooms, design D3 causes the droplets to spread in the entire room (Fig. 11c1). While design D1 and D2 shows relatively less spread of droplets in the room. Effect of air curtain on droplets dispersion can be seen from Fig. 11a2, 11b2 and 11c2 for design D1_AC, D2_AC and D3_AC respectively at 6 ACH ventilation rate.

From Fig. 11a2, it can be seen that air curtain air keeps the right volume of the room relatively clean compared to other designs. While rooms with design D2_AC and D3_AC show spread of droplets in whole room. Dispersion of droplets in the room with design D1, D2 and D3 at 15 ACH has been shown in Fig. 11d1, 11e1 and 11f1. At the high ventilation rate of 15 ACH, like previous time step of 20 s, droplets tend to accumulate near the walls on opposite sides. However, relatively
large number of small size droplets tend to diffuse on the left side of the room with design D2 at 15 ACH. Effect of air curtain in rooms with design D1_AC, D2_AC and D3_AC at 15 ACH ventilation rate has been shown in the Fig. 11d2, 11e2 and 11f2 respectively. Air curtain limits the spread of droplets more effectively in room with design D3_AC compared to D1_AC and D2_AC.

Similarly, Fig. 12 shows the dispersion of droplets in rooms of different designs (Table 1) at 6 ACH and 15 ACH. It shows that within 60 s duration, droplets spread in entire room in all designs irrespective of ventilation rate. High ventilation rate (15 ACH) spreads the droplets relatively more compared to 6 ACH due to high local air velocity. A qualitative observation of Figs. 9–12 indicate that most of the large size droplets (>50 μm) tend to deposit within first 20 s duration. While the cloud of smaller size particle rises upwards and spreads following the air streamlines. The outer ring of cloud is made of droplets ≤20 μm (approximately), due to higher drift velocity (Fig. 9). Each room shows a characteristic behavior, for example, early deflection of small size droplets towards the floor is achieved at 15 ACH (Fig. 9f1 and 9f2) in 10 s, while same effect is observed between 20 and 30 s at 6 ACH. Similarly, a comparable cloud behavior is observed at different time depending on ventilation rate on other room designs. Fig. 12 shows that rooms with 6 ACH ventilation need little longer to fill the room because of relatively low local air flow velocity.

5.4. Removal of sneeze droplets from room

As discussed in section 5.3, the sneeze droplets are subjected to deposition, evaporation, and escape following the ventilation air flow pattern and droplet size. Loss of droplets mass due to evaporation is primarily function of droplet and surrounding air temperature difference. Large size droplets deposit under the influence of gravity while the smaller size droplets deposit under influence of their momentum. Loss of mass due to escape is primarily dependent on streamlines, which terminate at exhaust. These processes lead to overall sneeze mass depletion. In an ideal condition, if a laminar flow could be achieved, loss of mass due to escape would be increased. However, ventilations flows are generally turbulent and mass depletion process is characterized by the indoor environment conditions. The fraction of sneeze mass deposited, evaporated, escaped and airborne in the room can be defined as follows:

\[
\text{Deposited mass (\%)} = \left(\frac{m_{\text{deposited}}}{m_{\text{total}}}\right) \times 100,
\]

\[
\text{Evaporated mass (\%)} = \left(\frac{m_{\text{evaporated}}}{m_{\text{total}}}\right) \times 100,
\]

\[
\text{Escaped mass (\%)} = \left(\frac{m_{\text{escaped}}}{m_{\text{total}}}\right) \times 100,
\]

\[
\text{Airborne mass (\%)} = \left(\frac{m_{\text{airborne}}}{m_{\text{total}}}\right) \times 100,
\]

The sneeze mass balance in room D3.AC at 15 ACH has been shown in the Fig. 13a. It shows that more than 95% of mass is depleted within 60 s. Remaining sneeze mass in the form of droplets (≤40 μm) spread in

![Graphs showing droplet distribution and sneeze mass depletion](image-url)
the room and remain airborne for a long time (Fig. 12). Fig. 13a shows that evaporation leads to the sneeze mass depletion (due to high droplet and room temperature difference) followed by deposition and escape processes. It can also be seen that escape contributes least to the mass depletion. A similar sneeze depletion pattern was observed for other rooms at both 6 ACH and 15 ACH ventilation rates.

A comparison of the evaporated, deposited, and escaped mass percentages for all rooms and two ventilation rates 6 ACH and 15 ACH has been shown in the Fig. 13b, Fig. c and Fig. d respectively. A qualitative comparison shows that room with dominant evaporation process shows less deposited mass percentage and vice versa. This observation suggests that high rate of evaporation reduces the weight of droplets. As a result, instead of depositing, droplet become lighter and tend to become airborne. High humidity in room can help to increase deposition of droplets.

5.5. Effect of HVAC configuration and ventilation rate on droplets of different size group

It is understood that aerosolized droplets deposit in upper and lower respiratory tracts depending on their size. Therefore, it becomes critically important to understand the removal of smaller size (<100 μm) droplets. Early removal of these droplets will reduce possibility of infecting any other person. Mass depletion processes are independent from each other and impact the population of droplets exclusively. Based on developed air flow patterns, each room shows unique droplets removal capabilities owing to HVAC configuration and ventilation rate. Their effect on droplets of population size groups 0 < d ≤ 10 μm, 10 < d ≤ 100 μm, 100 < d ≤ 500 μm, and d > 500 μm have been shown in Figs. 14–16.

Transient variation of number of droplets of diameter 0–10 μm has been shown in the Fig. 14a. It shows that D1 configuration keeps the droplets airborne for entire simulation time of 360 s, compared to D1_AC at 6 ACH. Air curtain accelerates effective removal of 0–10 μm droplets within first 160 s. Increase of ventilation rate to 15 ACH in both the configurations D1 and D1_AC performs better than D1 at 6 ACH, which is ultimately result of higher flow rates in the room. The inset of Fig. 14a shows comparison of number of airborne droplets for a period of 200–360 s after release in order to investigate the efficiency of removal. The color of histograms and graph indicators were kept same to represent the respective cases. It shows that D1_AC at 6 ACH demonstrate its consistent behavior of droplets removal.

Similarly, the transient variation of number of droplets of diameter range 10–100 μm has been shown in Fig. 14b. The high ventilation rate of 15 ACH efficiently removes more droplets compared to 6 ACH specially during 40–180 s duration, when droplets tending to spread homogeneously in room. Additionally, the Fig. 14b shows that air curtain further accelerate the removal of contaminated droplets from indoor environment of room. Fig. 14c and d shows airborne droplets of diameter range 100–500 μm and greater than 500 μm respectively at 6 and 15 ACH. Both figures show that large droplets are removed from room withing first few seconds. Ventilation rate has no effect on large droplets.
Fig. 15 shows transient variation of number of airborne droplets population in D2 and D2_AC at 6 and 15 ACH. Fig. 15a shows that room of design D2 at 6 ACH remove the droplets of size 0–10 μm very efficiently for initial 40 s, which depreciates thereafter. The aircurtain becomes more effective for this size group after 200 s, when just over more than 250 droplets are airborne. Due to high flow rate, 15 ACH performs better than 6 ACH in achieving cleaner indoor room environment. The inset of Fig. 15a show comparison of number of airborne droplets for a period of 200–360 s after release. D2_AC at 15 ACH is most efficient specifically when only few hundred droplets left in the room. The transient variation of number of droplets of diameter range 10–100 μm has been shown in the Fig. 15b. It shows that use of air curtain is beneficial for both the designs of room D2 and D2_AC at both the flow rates 6ACH and 15 ACH. The inset of Fig. 15b confirms that air curtain accelerates the removal of droplets. Fig. 15c–d shows transient variation of number of droplets of diameter range 100–500 μm and greater than 500 μm respectively. Large size droplets remain unaffected by the ventilation rates.

Fig. 15 shows transient variation of number of airborne droplets population in D2 and D2_AC at 6 and 15 ACH. Fig. 15a shows that room of design D2 at 6 ACH remove the droplets of size 0–10 μm very efficiently for initial 40 s, which depreciates thereafter. The aircurtain becomes more effective for this size group after 200 s, when just over more than 250 droplets are airborne. Due to high flow rate, 15 ACH performs better than 6 ACH in achieving cleaner indoor room environment. The inset of Fig. 15a show comparison of number of airborne droplets for a period of 200–360 s after release. D2_AC at 15 ACH is most efficient specifically when only few hundred droplets left in the room. The transient variation of number of droplets of diameter range 10–100 μm has been shown in the Fig. 15b. It shows that use of air curtain is beneficial for both the designs of room D2 and D2_AC at both the flow rates 6ACH and 15 ACH. The inset of Fig. 15b confirms that air curtain accelerates the removal of droplets. Fig. 15c–d shows transient variation of number of droplets of diameter range 100–500 μm and greater than 500 μm respectively. Large size droplets remain unaffected by the ventilation rates.

5.6. Role of HVAC ventilation in complete decontamination and droplets aerosol concentration variation

To prevent the spread of virus, it is necessary to remove every single aerosolized droplet from the indoor environment of room, which may be contaminated and contain large numbers of viral copies. Overall droplet removal percentage is very important and a critical function of HVAC configuration for achieving early decontamination. Percentage droplet number variation of droplets is shown in Figs. 17–19. Fig. 17a, b, 17c and 17d show variation of airborne droplets number percentage in room of design D3 and D3_AC at 6ACH and 15 ACH for the time period of (a) 0–5 s (b) 5–25 s, (c) 40–200 s and (d) 200–360 s. The color of histograms and graph indicators were kept same to represent the respective cases. Similarly, transient variation of number of droplets of diameter 10–100 μm in D3 and D3_AC at 6 ACH and 15 ACH have been shown in the Fig. 16b. It shows that air curtain accelerates droplets removal at 6 ACH. High ventilation rate of 15 ACH found most efficient. Comparison of droplets number for period of 200–300 s, shown in inset of Fig. 16b confirms that air curtain accelerates the removal of droplets. Fig. 16c–d transient variation of number of airborne droplets of diameter range 100–500 μm and greater than 500 μm respectively. The large droplet remain unaffected by ventilation rate and deposit early on surface.
5–25 s, effect of ventilation rate and air curtain begin to show. Air curtain is effective, when room is ventilated at 6 ACH. However, at 15 ACH, the effect of air curtain is more prominent in duration of 40–200 s, when droplets are sufficiently spread in the room by 40 s (Fig. 11). Modified air flow pattern due to air curtain effectively deposit more droplets on surfaces. Removal of widely dispersed micron size droplets is very difficult, however use of air curtain further improves the capability specially when less than 1% droplets remain airborne (Fig. 17d). Therefore, implementation of air curtain is important for these kind of rooms for removing droplets at low ventilation rate.

Fig. 18a, b, 18c and 18d show variation of airborne droplets number percentage at 0–5 s, 5–25 s, 40–200 s and 200–360 s respectively for room of design D2 and D2_AC at 6 ACH and 15 ACH ventilation rates. For the first 5 s, there is no effect of ventilation rates. In the period of 5–25 s, D2 and D2 AC at 6 ACH is more effective compared to high ventilation rate (Fig. 18b) because low flow rate allows deposition of relatively more droplets. However, as soon as droplets are spread in the room, the high ventilation rate leads the removal process mainly by deposition and escape. Fig. 18d for the period of 200–360 s show that air curtain improves the decontamination, specially, when small number of droplets are completely diluted in room indoor environment.

Fig. 19a, b, 19c and 19d shows variation of airborne droplets number percentage at 0–5 s, 5–25 s, 40–200 s and 200–360 s respectively for room of design D3 and D3.AC at 6 ACH and 15 ACH ventilation rates. Similar to previous cases, in first 5 s ventilation rate does not effect the droplets removal. In these kind of rooms, high ventilation rate (15 ACH) and use of air curtain further accelerate the droplets removal (Fig. 19b). In the period of 40–200 s, droplets cloud begin to move in downward direction (Fig. 8e and f) following the developed air streamlines (Figs. 6e, 7e and 6f, 7f). additionally, Fig. 13 indicate that in D3 AC at 15 ACH, rate of evaporation decreases, as a result, droplets remain large, acquire momentum and excessive deposit on surfaces (Fig. 19c). Fig. 19d also shows that air curtain is effective means of removal when droplets are low in number and completely diluted in room indoor environment.

The droplets aerosol concentration variation in rooms of different HVAC configuration has been shown in appendix 1, table A1. Transient variation of concentration variation show that air curtain can increase the droplet removal rate and hence the efficiency of decontamination.

6. Conclusion

New variants (e.g., Omicron) of the SARS-CoV-2 continue to emerge and may become more infectious. High positivity rate may cause more infections resulting in increased hospitalization. Studies have shown that SARS-CoV-2 can spread through aerosolized droplets. Therefore, HVAC configurations are critical for early decontamination of the room. In the present study, dispersion of sneeze droplets in hospital rooms of different HVAC configurations at 6 and 15 ACH ventilation rates have been modeled. The effect of diffuser, exhaust locations and implementation of air curtain has been investigated. The following conclusions can be drawn from the present study:

- Location of diffuser and exhaust are critical for flow patterns developed in the room. The ventilation rate of 6 ACH and 15 ACH generates a flow velocity of 0.1 m/s and 0.3 m/s respectively. Air curtain effectively modifies the flow pattern specially at 6 ACH ventilation rate.
- Sneeze droplets (0 < d ≤ 100 μm) initially form a cloud that keeps losing large droplets by different mass depletion mechanisms in the spreading process.
- Depending on HVAC configuration, evaporation, deposition, and escape can contribute maximum up to 68%, 36% and 2.5% respectively.
- HVAC configurations affect the removal of different droplet size groups uniquely. Droplet sizes 0 < d ≤ 10 μm are very sensitive to resuspension. However, droplet sizes 10 < d ≤ 100 μm are moderately affected, while large size droplets weakly correspond to ventilation.
- Transient droplets number percentage variation shows that in all room designs the effect of HVAC configuration is evident after the initial 5 s. The rapid decrease in airborne droplets is observed in 5–25 s, which is expected as large size droplets keep depositing.
- Droplets of sizes smaller than 50 μm become aerosolized and linger in ventilated indoor environment for a long time. Use of air curtain expedites removal of these micron droplets and reduces the droplets aerosol concentration in the room.
- Temporal and spatial initial spreading patterns exhibit a unique opportunity to capture the contaminated droplets before they completely dilute in indoor environment of room.

The results presented in this study can help mitigate the spread of infectious diseases in indoor environments.

Credit author statement

SK conducted the simulations and analyzed and interpreted computational modeling and analysis data. MDK and SK designed the study, MDK provided funding and both authors were major contributors to writing the manuscript. Both authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.113665.

Nomenclature

- k: turbulent kinetic energy (m$^2$s$^{-2}$)
- t: time (s)
- u: velocity (m/s)
- $F_D$: drag force (N)
- $Fx$: additional acceleration (N/m)


\[ \text{d} \quad \text{particle diameter (m)} \]
\[ C_d \quad \text{drag coefficient} \]
\[ Re \quad \text{Reynolds number} \]
\[ Sc \quad \text{Schmidt number} \]
\[ F \quad \text{Saffman force (N)} \]
\[ \nu \quad \text{velocity of air (m/s)} \]
\[ \nu_p \quad \text{velocity of particle (m/s)} \]
\[ dij \quad \text{deformation tensor} \]
\[ p \quad \text{pressure (Pa)} \]
\[ R \quad \text{gas constant (J/K/mol)} \]
\[ C_{pd} \quad \text{heat capacity of droplet (J/K)} \]
\[ T_d \quad \text{droplet temperature (K)} \]
\[ T_a \quad \text{air temperature (K)} \]
\[ u_x \quad \text{x-component of velocity (m/s)} \]
\[ u_y \quad \text{y-component of velocity (m/s)} \]
\[ u_z \quad \text{z-component of velocity (m/s)} \]
\[ x \quad \text{any distance in x direction along length of room (m)} \]
\[ y \quad \text{any distance in y direction along width of room (m)} \]
\[ z \quad \text{any distance in z direction along height of room (m)} \]

\[ \text{3D} \quad \text{three dimensional} \]

\textbf{Greek Symbols}

\[ \varepsilon \quad \text{Turbulent kinetic energy dissipation (m}^2\text{s}^{-3}) \]
\[ g \quad \text{acceleration due to gravity (m s}^{-2}) \]
\[ \rho \quad \text{density of air (kg m}^{-3}) \]
\[ \mu \quad \text{dynamic viscosity of air (m}^2\text{s}^{-1}) \]
\[ \nu \quad \text{kinematic viscosity (m}^2\text{s}^{-1}) \]
\[ \Delta \quad \text{difference in a quantity} \]

\textbf{Subscript}

\[ \text{eff} \quad \text{effective} \]
\[ k \quad \text{kinetic energy as in } k \]
\[ p \quad \text{particle} \]

**Appendix 1**

Table A1

| Time (s) | Droplets aerosol concentration variation (µg/m³) |
|---------|-----------------------------------------------|
|         | D1 | D1_AC | D2 | D2_AC | D3 | D3_AC | D1 | D1_AC | D2 | D2_AC | D3 | D3_AC |
| 0.2     | 290.55 | 290.59 | 288.48 | 289.68 | 289.08 | 287.86 | 289.41 | 291.22 | 292.03 | 291.77 | 290.10 | 290.05 |
| 2       | 144.53 | 145.13 | 147.02 | 146.02 | 141.08 | 151.58 | 149.26 | 149.30 | 153.47 | 159.52 | 153.57 | 148.70 |
| 5       | 43.07  | 44.51  | 46.80  | 43.79  | 40.49  | 49.68  | 46.04  | 48.99  | 55.19  | 60.82  | 50.56  | 46.06  |
| 10      | 13.58  | 13.07  | 13.58  | 13.03  | 14.93  | 17.04  | 12.76  | 14.72  | 16.58  | 18.51  | 16.08  | 15.19  |
| 20      | 9.24   | 8.18   | 8.68   | 9.24   | 12.30  | 12.81  | 8.68   | 8.85   | 9.83   | 9.91   | 9.89   | 9.89   |
| 40      | 6.30   | 5.65   | 6.78   | 7.05   | 9.89   | 10.78  | 6.29   | 6.42   | 7.00   | 6.28   | 5.08   | 5.29   |
| 60      | 4.67   | 3.71   | 5.04   | 5.29   | 8.24   | 8.42   | 4.22   | 4.60   | 4.63   | 3.72   | 3.07   | 3.50   |
| 100     | 2.84   | 1.52   | 2.93   | 2.88   | 5.87   | 5.27   | 2.00   | 2.20   | 2.22   | 1.55   | 1.36   | 1.80   |
| 140     | 1.92   | 0.79   | 1.81   | 1.74   | 4.17   | 3.42   | 0.93   | 1.04   | 1.09   | 0.67   | 0.61   | 0.90   |
| 180     | 1.33   | 0.47   | 1.17   | 1.07   | 2.82   | 2.23   | 0.46   | 0.46   | 0.51   | 0.30   | 0.30   | 0.43   |
| 200     | 1.11   | 0.36   | 0.97   | 0.86   | 2.32   | 1.78   | 0.33   | 0.31   | 0.39   | 0.21   | 0.21   | 0.30   |
| 240     | 0.95   | 0.21   | 0.65   | 0.52   | 1.60   | 1.18   | 0.16   | 0.13   | 0.18   | 0.11   | 0.11   | 0.14   |
| 280     | 0.57   | 0.13   | 0.43   | 0.32   | 1.13   | 0.73   | 0.09   | 0.06   | 0.09   | 0.05   | 0.05   | 0.08   |
| 320     | 0.40   | 0.08   | 0.31   | 0.22   | 0.81   | 0.45   | 0.04   | 0.03   | 0.04   | 0.02   | 0.02   | 0.04   |
| 360     | 0.27   | 0.06   | 0.21   | 0.16   | 0.55   | 0.28   | 0.03   | 0.01   | 0.02   | 0.01   | 0.02   | 0.02   |

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