Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Influence of indoor airflow on particle spread of a single breath and cough in enclosures: Does opening a window really ‘help’?

M.R.R.S. van Beest a,b, F. Arpino c, O. Hlinka d, E. Sauret f, N.R.T.P. van Beest b, R.S. Humphries e, G. Buonanno c, L. Morawska g, G. Governatori h, N. Motta a,*

a School of Chemistry and Physics, Queensland University of Technology, Brisbane, Australia
b School of Mechanical, Medical and Process Engineering, Queensland University of Technology, Brisbane, Australia
c Climate Science Centre, CSIRO Oceans and Atmosphere, Aspendale, Victoria, Australia
d Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, Italy
e Information Management & Technology (IM&T), CSIRO, Pullenvale, Queensland, Australia
f School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane, Australia

A B S T R A C T

The spread of respiratory diseases via aerosol particles in indoor settings is of significant concern. The SARS-CoV-2 virus has been found to spread widely in confined enclosures like hotels, hospitals, cruise ships, prisons, and churches. Particles exhaled from a person indoors can remain suspended long enough for increasing the opportunity for particles to spread spatially. Careful consideration of the ventilation system is essential to minimise the spread of particles containing infectious pathogens. Previous studies have shown that indoor airflow induced by opened windows would minimise the spread of particles. However, how outdoor airflow through an open window influences the indoor airflow has not been considered. The aim of this study is to provide a clear understanding of the indoor particle spread across multiple rooms, in a situation similar to what is found in quarantine hotels and cruise ships, using a combination of HVAC (Heating, Ventilation and Air-Conditioning) ventilation and an opening window. Using a previously validated mathematical model, we used 3D CFD (computational fluid dynamics) simulations to investigate to what extent different indoor airflow scenarios contribute to the transport of a single injection of particles (1.3 μm) in a basic 3D multi-room indoor environment. Although this study is limited to short times, we demonstrate that in certain conditions approximately 80% of the particles move from one room to the corridor and over 60% move to the nearby room within 5 to 15 s. Our results provide additional information to help identifying relevant recommendations to limit particles from spreading in enclosures.

1. Introduction

Indoor environments are contributing to the potential risk of spreading an infectious disease, as the likelihood of infected people sharing the same air with other people is high (Morawska et al., 2020). As poorly ventilated areas also contribute to particles remaining suspended in the air for longer periods (Jo et al., 2019; Kulkarni et al., 2016; Rule et al., 2018), the removal of the particles containing infectious pathogens from indoor air by ventilation is therefore essential to prevent the spread of respiratory diseases, such as, severe acute respiratory syndrome (SARS) epidemic in 2003, H1N1 influenza epidemic in 2011 and Middle East respiratory syndrome (MERS) outbreak and the current 2020 SARS-CoV-2 pandemic (Qian and Zheng, 2018; Morawska and Cao, 2020). It is also important to lower the concentration of the more important indoor contaminants, such as, tobacco smoke, radon decay products, combustion gases, formaldehyde, asbestos fibres, microorganisms, and aeroallergens, which are associated with adverse health and irritation effects among asthmatic people in particular (Spengler and Sexton, 1983; Berglund et al., 1992; Canova et al., 2010; Yu et al., 2000). Diseases can be transmitted from host to host in different ways. While viruses are smaller than a micron, they usually settle on large particles, such as water, proteins, salts and other components (Blachere et al., 2009; Dietz et al., 2020). Particles that may contain infectious pathogens (Wilson, 2006) have diameters that can range from <1 μm to a few millimetres. These particles can become...
escape via the window and reduced the particle movement across window in a classroom near an infected teacher allowed particles to remain suspended in the air for several minutes in a supermarket. One numerical study showed that particles exhaled from a person can influence the movement of particles as numerous studies already have shown (Li et al., 2020b; Qian and Zheng, 2018; Shao et al., 2021).

In indoor environments, different airflow scenarios can significantly affect the spread of particles. For example, in hotels as there are multiple cases of people on the same floor or next from one room to another, which was also suggested in quarantine hotels and cruise ships. Reports suggested that viruses transported by the airflow can move by using the Lagrangian Particle Tracking (LPT) approach, based on a disperse dilute two-phase flow (Yeoh and Tu, 2019). The spacing between particles is sufficiently large and the volume fraction of micrometer sized particles with the room is small enough (<10⁻³) to justify the use of a Eulerian-Lagrangian approach, in which the continuum equations are solved for the airflow (continuously phase) and Newton’s equation of motion is solved for each particle as is done in Cortellessa et al. (2021). The continuum equations of mass and momentum solved for an unsteady incompressible Newtonian flow are not provided as they are widely available in the scientific literature (Arpino et al., 2014; Massarotti et al., 2006; Scungio et al., 2013; Versteeg and Malalasekera, 2007). As the Reynolds Number in our simulation setup is larger than 4000 (Re_window = 58,192), we have included Reynolds Averaged Simulation (RAS) turbulence based on the linear eddy viscosity turbulence model k−ω Shear Stress Transport (SST), which is also widely described in the literature (Versteeg and Malalasekera, 2007; Argyropoulos and Markatos, 2015). We used the standard wall function for modelling the airflow near the walls. In all simulations, we used the Crank Nicholson temporal scheme, Gauss linear corrected laplacian scheme, the Gauss linear gradient scheme, a linear interpolation scheme and the divergence scheme for phi was Gauss upwind. The default linear interpolation scheme was adopted while as a linear solver the GAMG (Geometric agglomerated algebraic multi-grid solver) was used.

Nomenclature

| Symbol | Definition |
|--------|------------|
| 𝐶 | Heating, Ventilation and Air-Conditioning |
| CFD | Computational Fluid Dynamics |
| LPT | Lagrangian Particle Tracking |
| RAS | Reynolds Averaged Simulation |
| SST | Shear Stress Transport |
| m_d | Particle mass [kg] |
| u_d | Particle velocity [m/s] |
| t | Time [s] |
| F_D | Drag force [N] |
| F_G | Gravity force [N] |
| n | Outgoing normal |
| d_x | Particle trajectory [m] |
| u | Flow velocity [m/s] |
| ρ_d | Particle density [kg m⁻³] |
| d_d | Particle diameter [m] |
| 𝑅𝑒_d | Reynolds number particle |
| C_D | Drag coefficient |
| m | Mass flow rate [kg/s] |
| ρ | Air density [kg m⁻³] |
| v | Injector flow velocity [m/s] |
| A | Cross-sectional area in/outlet [m²] |
| d_in | Diameter injector [m] |

The transmission of particles can be over short and long distances. A transmission distance of <1 m between people is considered to be a short distance and covers transmissions caused by social interaction in close proximity (breathing, speaking, coughing and sneezing). Transmission of particles over longer distances are mainly influenced by indoor airflow. Indoor air ventilation, movement of people and temperature differences all have an impact on the indoor airflow (Tang et al., 2006).

In still air, the time in which airborne particles settle on the ground depends primarily on the diameter of the particle as that directly affects the gravitational force. While particles with a diameter >50 μm (also know as droplets) will almost immediately settle on surfaces, it will take intermediate-sized particles or droplets (10–50 μm) up to several minutes to settle. Even smaller particles, with a diameter of <10 μm, can remain airborne for hours and can be inhaled by persons (Blachere et al., 2009). For instance, the SARS-CoV-2 virus is able to spread widely in confined enclosures (Mizumoto et al., 2020), like hospitals (Gan et al., 2020), cruise ships (Rocklov et al., 2020), prisons (Burki, 2020), churches (Shim et al., 2020), restaurants (Li et al., 2020a), classrooms and trains (Wang et al., 2022). Regarding the spread on cruise ships, there is a report from passengers describing that they opened the balcony door and the door to corridor to provide fresh air to the opposite rooms (McFall-Johnsen, 2020). Some reports suggested that viruses transported by the airflow can move from one room to another, which was also suggested in quarantine hotels as there are multiple cases of people on the same floor or next door of that got infected (Layt, 2021; Nothing, 2021; Taylor, 2021).

In indoor environments, different airflow scenarios can significantly influence the movement of particles as numerous studies already have shown (Li et al., 2020b; Qian and Zheng, 2018; Shao et al., 2021). One numerical study showed that particles exhaled from a person can remain suspended in the air for several minutes in a supermarket aisle (Vuorinen et al., 2020). Another study showed that opening the window in a classroom near an infected teacher allowed particles to escape via the window and reduced the particle movement across the room considerably (Ahmadzadeh et al., 2021). Other numerical studies also provide knowledge about identification of critical particle spread scenarios in passenger trains (Ahmadzadeh and Shams, 2021), in airplanes (Talaat et al., 2021) and in elevators (Dbouk and Drikakis, 2021). However, the influence of outdoor wind velocity through an opened window impacting the indoor airflow has not been considered in the current literature.

This CFD (Computational Fluid Dynamics) study aims to investigate to what extent indoor airflow, influenced by either an HVAC (Heating, Ventilation and Air-Conditioning) system and/or open window, contributes to the transport of particles in a basic 3D multi-zone environment, similar to what is found in quarantine hotels and cruise ships. The mathematical validated particle tracking model from Cortellessa et al. has been used in this CFD study (Cortellessa et al., 2021). While the focus is on particles originating from a breath or cough, the results may also help to better understand how to control the airflow to minimise the spread of particles in general across multiple rooms.

The remainder of this paper is structured as follows. Section 2 describes the numerical method used for the simulations as well as the boundaries of the domain. Subsequently, we discuss the detailed results for the various scenarios in Section 3. Finally, we discuss the implications of this study along with practical suggestions for limiting the spread of particles in Section 4.

2. Methods

2.1. Mathematical model

The CFD model is developed using the open source OpenFOAM toolbox (OpenCFD Ltd., 2021) to simulate the particle movement from a single injection over time. The velocity, pressure and temperature fields along with the particle motion and interaction with the fluid were obtained. The particle motion inside the airflow was modelled by using the Lagrangian Particle Tracking (LPT) approach, based on the divergence scheme for phi was Gauss upwind. The default linear temporal scheme, Gauss linear corrected laplacian scheme, the continuum equations of mass and momentum solved for an unsteady incompressible Newtonian flow are not provided as they are widely available in the scientific literature (Arpino et al., 2014; Massarotti et al., 2006; Scungio et al., 2013; Versteeg and Malalasekera, 2007). As the Reynolds Number in our simulation setup is larger than 4000 (Re_window = 58,192), we have included Reynolds Averaged Simulation (RAS) turbulence based on the linear eddy viscosity turbulence model k−ω Shear Stress Transport (SST), which is also widely described in the literature (Versteeg and Malalasekera, 2007; Argyropoulos and Markatos, 2015). We used the standard wall function for modelling the airflow near the walls. In all simulations, we used the Crank Nicholson temporal scheme, Gauss linear corrected laplacian scheme, the Gauss linear gradient scheme, a linear interpolation scheme and the divergence scheme for phi was Gauss upwind. The default linear interpolation scheme was adopted while as a linear solver the GAMG (Geometric agglomerated algebraic multi-grid solver) was used.

For various reasons described in the Supplementary Material, several forces can be neglected. The particle motion is described by solving the following LPT equation:

$$m_d \frac{du_d}{dt} = F_D + F_G$$

(1)

and

$$\frac{dx_d}{dt} = u_d$$

(2)
where \( m_d \) [kg] is the mass of the particle; \( \mathbf{u} \) \( \frac{m}{s} \) represents the particle velocity; \( t \) [s] is the time; \( F_D \) [N] and \( F_G \) [N] are, respectively, the drag and gravity forces acting on the particle; and \( d_x \) [m] represents the trajectory of the particle. The drag force is given by (Crowe et al., 1980):

\[
F_D = m_d \frac{18}{\rho_d \cdot d_x^2} C_D \frac{Re_D}{24} (\mathbf{u} - \mathbf{u}_x)
\]  

(3)

In Eq. (3), \( \mathbf{u} \) \( \frac{m}{s} \) represents the flow velocity, while \( \rho_d \) [kg m\(^{-3}\)], \( d_x \) [m] and \( Re_D \) represent, respectively, the density, diameter and Reynolds number of the particle. The latter is calculated as:

\[
Re_D = \frac{\rho (|\mathbf{u} - \mathbf{u}_x|) d_x}{\mu}
\]  

(4)

whereas the drag coefficient, \( C_D \) in Eq. (3), is evaluated as a function of the particle Reynolds number:

\[
C_D = \begin{cases} 
\frac{24}{Re_D} & \text{if } Re_D < 1 \\
\frac{24}{Re_D} \left( 1 + 0.15 \cdot Re_D^{0.667} \right) & \text{if } 1 \leq Re_D \leq 1000 \\
0.44 & \text{if } Re_D > 1000
\end{cases}
\]  

(5)

Particle collisions are considered to be elastic and the equations of motion for the particles are solved assuming a two-way coupling: the flow field affects the particle motion and vice-versa.

The proposed investigations represent an application to room scale interaction of the mathematical and numerical models recently applied in Cortellessa et al. (2021) to investigate close proximity risk assessment for SARS-CoV-2 infection and has been thoroughly validated against experiments. They proved the reliability of the employed model by comparing numerical results with Particle Image Velocimetry (PIV) measurement results for respiratory activities (breathing and speaking). For breathing activity, the peak numerical and experimental peak measurement results for respiratory activities (breathing and speaking) by comparing numerical results with Particle Image Velocimetry (PIV) against experiments. They proved the reliability of the employed model. The assessment for SARS-CoV-2 infection and has been thoroughly validated in Cortellessa et al. (2021) to investigate close proximity risk.

2.1.2. Computational domain and boundary conditions

As the layout of every commercial building and cruise ships differ from each other, it is important to minimise the number of domain-related variables that are potentially influencing particles from spreading in different manners. Therefore, a basic symmetrical layout was designed for simulating and comparing the influence of different indoor airflow scenarios as shown in Fig. 1.
Evaporation has a significant effect on the diameter of particles from a breath or cough. We tested particles with multiple sizes and those with a diameter of 10 μm and smaller do not settle quickly on the surfaces and have similar spread behaviour, in line with Vuorinen et al. (2020). These particles are able to stay airborne for long periods of time and have the ability to reach the alveolar region of the lungs when inhaling (Jamriska and Morawska, 2003; Lindsley et al., 2012; ACGIH, Hygienists and others, 2009). We are interested in those particles as they can transmit diseases over longer distances than larger particles (Chartier and Pessoa-Silva, 2009; Bourouiba et al., 2014). In our simulations, post-evaporation particles were assumed to be spherical with a diameter of 1.3 μm which is about the median of the particles’ nuclei size (0.74–2.12 μm) reported in Yang et al. (2007). We used the density of water (998.2 kg m⁻³), as the composition of particles released by a cough or a breath is dominated by water and/or solutions of organics with a similar density (Johnson et al., 2011; Effros et al., 2020).

Evaporation has a significant effect on the diameter of particles from a breath or cough. We tested particles with multiple sizes and those with a diameter of 10 μm and smaller do not settle quickly on the surfaces and have similar spread behaviour, in line with Vuorinen et al. (2020). These particles are able to stay airborne for long periods of time and have the ability to reach the alveolar region of the lungs when inhaling (Jamriska and Morawska, 2003; Lindsley et al., 2012; ACGIH, Hygienists and others, 2009). We are interested in those particles as they can transmit diseases over longer distances than larger particles (Chartier and Pessoa-Silva, 2009; Bourouiba et al., 2014). In our simulations, post-evaporation particles were assumed to be spherical with a diameter of 1.3 μm which is about the median of the particles’ nuclei size (0.74–2.12 μm) reported in Yang et al. (2007). We used the density of water (998.2 kg m⁻³), as the composition of particles released by a cough or a breath is dominated by water and/or solutions of organics with a similar density (Johnson et al., 2011; Effros et al., 2002).

Evaporation has a significant effect on the diameter of particles from a breath or cough. We tested particles with multiple sizes and those with a diameter of 10 μm and smaller do not settle quickly on the surfaces and have similar spread behaviour, in line with Vuorinen et al. (2020). These particles are able to stay airborne for long periods of time and have the ability to reach the alveolar region of the lungs when inhaling (Jamriska and Morawska, 2003; Lindsley et al., 2012; ACGIH, Hygienists and others, 2009). We are interested in those particles as they can transmit diseases over longer distances than larger particles (Chartier and Pessoa-Silva, 2009; Bourouiba et al., 2014). In our simulations, post-evaporation particles were assumed to be spherical with a diameter of 1.3 μm which is about the median of the particles’ nuclei size (0.74–2.12 μm) reported in Yang et al. (2007). We used the density of water (998.2 kg m⁻³), as the composition of particles released by a cough or a breath is dominated by water and/or solutions of organics with a similar density (Johnson et al., 2011; Effros et al., 2002).
Fig. 2. Results simulation C-10: Screenshots of a single cough particle spread with the particle injector near the door of Room 2, open window with 1 m/s airflow outwards, and HVAC inlet and outlet airflow rates of 20 L/s. The three graphs at the bottom provide information about the particle spread in certain zones over a time period of 60 s.

by turbulent air movements \((\text{Re}_{\text{window}} = 58192, \text{Re}_{\text{inj}} = 19973)\) and convection (Gensdarmes, 2015). We defined the temperature of the flow of the injector to be 307.5 K (34.5 °C) as that is the average measured value for human coughs and breaths (Cowan et al., 2010). The temperature of the air and the particles in the domain was set to 293 K (20 °C).

We differentiated between a single breath and a single cough to analyse the influence of the initial particle velocity on the particle spread. To approximate a single cough, we injected 40,000 particles during a single cough as done in a similar study (Vuorinen et al., 2020), which is within range of reported values from coughing patients with influenza in another paper (Lindsley et al., 2012). The initial particle velocity for a human cough, as measured in multiple studies varies between 6 and 22 m/s (Tang et al., 2012). In each of the single cough simulations we used the initial particle velocity of 6 m/s, the lower end of this velocity range. Although the number of particles measured in a breath is in reality much smaller compared to a cough (Fabian et al., 2011), we only differentiated a breath from a cough by its velocity difference. In each of the single breath simulation, an initial particle velocity of 0.3 m/s was used as that value is measured to be on the lower end of a breath velocity through an opened mouth (Tang et al., 2013). In quarantined facilities, doors of the room are only opened for a short period of time to minimise spread of particles. Therefore, we are interested in the airflow scenarios in which even particles with a low initial velocity are able to spread across the domain in a short period of time.

For statistical purposes, the duration of each particle injection, including the inlet airflow from a single cough or breath, is 0.5 s in both the single breath and cough scenarios. Using the injector diameter, injector durations of 0.5 s and the injector flow velocity, the mass flow rate for a single cough \(1.352 \times 10^{-02} \text{ kg/s}\) and breath \(6.762 \times 10^{-04} \text{ kg/s}\) was calculated.

2.2. Simulations cases

Using the domain and particle related settings described above, two sets of twelve different airflow scenarios were composed to analyse the particle spread. One set for a single breath and one for a single cough, as we were interested in the effects of a different initial velocity of the particles which is influenced by the flow from the breath or cough velocity. We used two different HVAC airflow settings: a flow rate of 20 L/s (which is corresponding to a velocity of 0.125 m/s) which is conform standard AS1668.2-2012 (Standards Australia, 2012) and a doubled value (0.250 m/s) to investigate the influence of airflow rates on the particle spread. The window can be closed or opened, causing an airflow with an inwards or outwards direction with a velocity of 1 m/s for reasons described earlier. In Table 2, a complete overview is shown of the simulation cases.
2.3. Mesh independence analysis

To make sure that the mesh/grid resolution does not affect the results we conducted a mesh independence study. Mesh independence is achieved when there is a negligible change in results with mesh density. The geometry of the domain used for the simulations (as shown in Fig. 1) and the computational grid was generated employing the open-source software SALOME 9.4 (Open Cascade, 2005-2021). The simulation scenario with an opened window has the highest consistent airflow velocity and was used for this analysis. Three different mesh sizes have been generated for the mesh sensitivity analysis: 4 million cells, 8.1 million cells and 16.7 million cells. In Table ST-1, a complete overview is provided of the three meshes and their grid parameters, non-orthogonality, skewness factor and the y+ value near the walls.

For analysing the mesh independence between the three meshes, we compared four velocity profiles in the middle of the rooms as the mesh is refined near the walls (see the red lines V1–V4 in Figure SF-1). We excluded the influence of the single cough or breath during this analysis.

After simulating the three meshes in steady state, the relative velocity errors from velocity profiles from Figure SF-1 have been computed as follows:

$$\delta_{\text{Mesh 1 to 2}} = \frac{|v_{\text{Mesh 1}} - v_{\text{Mesh 2}}|}{v_{\text{Window}}} \times 100\%$$

where $\delta_{\text{Mesh 1 relative to 2}}$ is the velocity percentage error, $v_{\text{Mesh 1}}$ is the velocity from velocity profile of Mesh 1, $v_{\text{Mesh 2}}$ is the velocity from velocity profile of Mesh 2 and $v_{\text{Window}}$ is the velocity at the window (1 m/s). In Table ST-2 the maximum and average velocity errors from the four velocity profiles in all directions are provided.

When comparing the velocity error between the three meshes, Mesh 2 proved to be sufficiently accurate with a maximum relative velocity error of less than 5% and a relative average velocity error of less than 1%. A detailed picture of Mesh 2 is shown in Figure SF-2.

2.4. Time step independence analysis

Our simulations are considered to be transient as the flow changes over time due to the single breath or cough. To minimise the temporal error we conducted a time step independence study. We performed a time step independence analysis using Mesh 2, employing three different time step sizes: 0.04 s, 0.02 s and 0.01 s. Simulations proceeded until steady state condition was reached. For analysing the time step independence between the three time step sizes, we compared five velocity probes P0-P4 from Figure SF-1.

The relative velocity errors from the five velocity probes have been computed as follows:

$$\delta_{\text{Time step 0.04 relative to 0.02}} = \frac{|v_{\text{Time step 0.04}} - v_{\text{Time step 0.02}}|}{v_{\text{Window}}} \times 100\%$$

where $\delta_{\text{Time step 0.04 relative to 0.02}}$ is the velocity percentage error, $v_{\text{Time step 0.04}}$ is the velocity from time step profile of Time step 0.04 s, $v_{\text{Time step 0.02}}$ is the velocity from time step profile of Time step 0.02 s and $v_{\text{Window}}$ is the velocity at the window (1 m/s).
Fig. 4. Results simulation C-01: Screenshots of a single cough particle spread with the particle injector in the centre of Room 2 in direction of the corridor, closed window, and HVAC inlet and outlet airflow rates of 20 L/s. The three graphs at the bottom provide information about the particle spread in certain zones over a time period of 60 s.

2.5. Particle spread simulation setup

In our particle spread simulations, there are four different particle injection locations. Therefore, four meshes have been generated using the mesh parameters of Mesh 2 (with the particle injector location as the only difference). Each grid of the nearly 90 m$^3$ domain is composed of 8.1 million tetrahedral cells. As described in Section 2.1.2, we included a temporary mass flow rate from the lungs during the single particle injection. Therefore, we performed the simulations in transient mode for tracking the particles for 60 s.

Note that in the transient mode we started the particle injection (including the mass flow rate from the lungs for 0.5 s) after the airflow (induced by the opened window and HVAC inlets and outlets) has stabilised. A stable airflow was reached after about 340 s. Using the previously calculated time step of 0.02 s, the duration of each simulation was set to 400 s with a particle injection taking place from 340 s for 0.5 s. As these 340 s will not be part of the analysis of the results, we have defined the time at which particles are being injected to be at Time = 0 s.

3. Results and discussion

As previously described, the reliability of the employed model has been proven in Cortellessa et al. (2021) by comparing numerical results with Particle Image Velocimetry (PIV) measurement results for respiratory activities (breathing and speaking). Throughout the remainder of this paper, we will refer to the following three zones within the domain:

- The room of origin: consists of the volume of the room where particles are being injected, which is either Room 1 or Room 2,
- The corridor: consists of the volume of the corridor including the volume underneath the door posts,
- The opposite room of origin: consists of the room opposite to the particles’ origin room.

Using the coordinate data from the simulation results, the location of the particles with respect to the three volumes described above have been compared over time. The percentage of particles leaving
the domain via the HVAC outlets was also taken into account. We are interested in the extreme cases that will either minimise or maximise the spread of the particles across the domain. The 3D visualisation of six simulation cases will be shown to provide a general understanding of the cases in which particles either stay in the room of origin or spread within the domain to other zones.

3.1. Airflow scenarios for a single cough

The worst-case scenario is that of a single cough near the door of Room 2 with an opened window and 1 m/s flow outwards, where HVAC flow rates of all inlets and outlets are set to 20 L/s (simulation C-10). After 5 s there is a peak corresponding to about 90% of the particles moved to the corridor (see Fig. 2a). At around 10 s into the simulation, about 60% of the particles travel outside of Room 2 to the corridor within 5 s, particles do not travel to the opposite Room 1 and mainly stay suspended in the air near the door post of Room 2. As the induced airflow by the HVAC system is close to stationary near the door posts, particles almost immediately slow down after the cough to the local airflow and do not travel further than the door post by 60 s. About 10% are being exhausted from Room 2 within 60 s via the HVAC outlet.

The best-case airflow scenario for a single cough is with a closed window and HVAC flow rates of all inlets and outlets being set to 20 L/s (C-01). In this case the particles do not travel outside Room 2 after being injected in the centre of the room in direction of the corridor. Rather, they remain floating in the air and spread slowly through the room (see Fig. 4). Similar to the case C-10, nearly 10% of the particles are being exhausted from Room 2 within 60 s from the domain.

3.2. Airflow scenarios for single breath

The initial velocity of a breath is lower than for a single cough (0.3 m/s versus 6 m/s) and we are interested in scenarios capable of moving particles to the corridor and opposite room. B-10 simulation is similar to C-10, with an open window, 1 m/s flow onwards and HVAC flow rates of all inlets and outlets equal to 20 L/s. However, in this case
Atmospheric Pollution Research 13 (2022) 101473

M.R.R.S. van Beest et al.

Fig. 6. Results simulation B-08: Screenshots of a single breath particle spread with the particle injector near the door of Room 1 in direction of the corridor, open window with 1 m/s airflow inwards, and HVAC inlet and outlet airflow rates of 20 L/s. The three graphs at the bottom provide information about the particle spread in certain zones over a time period of 60 s.

we consider a single breath opposed to a single cough. After 5 s, about 45% of the particles are in the corridor (see peak in Fig. 5a). At around 10 s, 30% of the particles travel to Room 1 (see Fig. 5b), while 20% of the particles remain in the corridor and 50% in Room 2. At 60 s, there are still no particles exhausted from the domain, either through opened window or the HVAC outlets (see Fig. 5c).

Fig. 6 shows the simulation B-08, a mirrored airflow scenario of the previous B-10. In B-08 we set an opened window in Room 2 with an inwards airflow of 1 m/s, while particles are being injected near the door in Room 1 in direction of the corridor. The HVAC flow rates of all inlets and outlets have been set to 20 L/s as well. As can be seen in Fig. 6, 80% of the particles are travelling to the corridor within 15 s. About 7.5% of the particles are found in Room 2 by 10 s and 30% end up in the corridor within 30 s. After 60 s over 60% of the particles are being exhausted by the HVAC outlets.

The last airflow scenario presented is B-07 (see Fig. 7), which is the same as B-08 but with a different injection point, the centre of Room 1. In this case 45%-55% of the particles move to the corridor in 7 s. Within 10 s about 20% of the particles are found in Room 2. By 30 s 25% of the particles are present at both ends of the corridor. After 60 s nearly 60% of the particles are being exhausted by the HVAC outlets leaving 20% of the particles in the corridor and 10% in the opposite Room 2. This shows that in case of an opened window particles with a very low initial velocity are still able to find their way to the corridor and the opposite room.

3.3. Particles escaping the domain

We also investigated through which HVAC exhaust the particles from a single breath or cough escaped the domain. In graphs a, b and c from Figure SF3, the percentage of escaped particles from a single breath via the different exhausts is plotted as a function of time in the different airflow scenarios (see graphs a, b and c). Cases in which <1% of the particles were leaving the domain have been omitted from this overview to improve clarity. There are only two scenarios in which particles are escaping the domain via the HVAC exhaust in Room 1, with about 10% of the particles escaping the domain in B-07 and less than 2% in B-08. More particles are escaping via the HVAC exhaust in Room 2, with over 80% of the particles escaping the domain in scenario B-12. After 60 s 50% of the particles escaped the domain in scenario B-02, whereas 70% escaped in the scenario B-04 with the doubled HVAC flow rate of 40 L/s. After 25 s 20% of the particles escaped the domain in scenario B-07, and nearly 10% in scenario B-08. Only in scenario B-07 and B-08 particles escaped via the corridor HVAC exhaust; with over 50% of the particles escaping the domain in scenario B-08 and nearly 30% in scenario B-07.
For the case of particles from a single cough escaping the domain, graphs d, e and f from Figure SF-3 show the percentage of escaped particles via the different exhausts plotted as a function of time in the different airflow scenarios (see graphs d, e and f). There are only two scenarios in which particles escape the domain via the HVAC exhaust in Room 1, with about 10% of the particles escaping the domain in C-07 and less than 2% in C-08. More particles are escaping via the HVAC exhaust in Room 2, with nearly 90% of the particles escaping the domain in scenario C-12, about 20% of the particles escaping the domain in scenario C-07, and nearly 10% in scenario C-08 and C-11. In scenarios C-01 and C-02, only about 9% and 11% of the particles escaped the domain, respectively. Scenarios C-03 and C-04 with the double HVAC flow rate increased the percentage of particles being exhausted from the domain to 15% and 17%, respectively. In general, an inwards window airflow showed to have a dominant effect on the number of particles escaping the domain via the HVAC exhausts. In closed window scenarios, particles from a single breath (with a low initial particle velocity and injector flow) injected underneath an HVAC exhaust are exhausted from the domain within 60 s. Although doubling the HVAC flow rates also contributed to more particles being exhausted from the domain, for effective particle removal the HVAC flow rate should be increased even more by using air changes per hour as is common practice in hospitals (Standards Australia, 2012).

### 3.4. General airflow behaviour

The general observed airflow phenomena in the performed simulations confirms that an open window with a 1 m/s airflow velocity inwards provides a dominant effect with respect to the particle movement between the rooms. Fig. 8 shows an overview of the fluid flow using velocity vectors in case of a closed and opened window. In case of a closed window (see Fig. 8a) the velocities are lower compared to an opened window. Across the domain, the airflow is near stationary due to the closed window. The HVAC velocity is not significant to transport particles between the room and corridor in a short period of time. In case of the opened window with an outwards airflow velocity of 1 m/s (see Fig. 8b), the general direction of the airflow in Room 1 is towards the window, while the airflow in the centre of Room 1 is near stationary. The airflow near the door of Room 2 is in direction of the corridor and able to transport particles to Room 1 (see simulation B-10). However, the airflow in the centre of Room 2 is also near stationary with a recirculating airflow next to the walls. Fig. 8c shows a dominant influence on the indoor airflow when the window is opened with the airflow coming in, providing a greater ability to transport particles across the domain. While in all airflow scenarios continuously open doors are assumed, the effect of vortices created by opening a
hinged door will likely have additional influences on particle movement towards the corridor (Tang et al., 2005).

4. Conclusion

In this paper, we used fluid dynamic modelling to analyse the influence of indoor airflow on particle movement originating from a human cough or breath inside enclosures – a critical issue in cruise ships and in quarantined facilities.

We showed that an opened window has a dominant effect on the indoor airflow and contributes to the transport of particles across multiple rooms within seconds; even when considering a wind speed of only 1 on the scale of Beaufort. In case of an opened window, we showed that when air flows from the particle source in the direction of the corridor, particles from a single breath or cough have the ability to be spread across the entire domain. In all airflow scenarios involving a closed window, only when a single cough was located near the door of a room, particles were able to move out of the room into the corridor. In case of a single breath, particles in all closed window scenarios stayed in the room of origin.

Generally, the airborne transmission process could be divided into two stages, a short-range stage (a spread of less than 2 m) and a
second long-range stage. The first stage is strongly influenced by the initial releasing direction and velocity of the particles. However, the second stage is mainly controlled by the airflow conditions in space. Therefore, the particle spread across multiple rooms is mainly affected by the ventilation flow conditions, not the initial releasing conditions of the particles. Doubling the HVAC flow rates also contributed to more particles being exhausted from the domain in the closed window setting, but for effective particle removal the HVAC flow rate should be increased even more by using air changes per hour as is common practice in hospitals (Standards Australia, 2012). Although our study is limited to modelling a short time span, the vast majority of the particles can travel to the corridor and opposite room in 5–10 s in case of an open window (up to 55% of the particles for an outwards window airflow, and 80%–90% for an inwards window airflow). As doors in quarantined facilities are usually only opened for short periods of time, we find that running simulations for longer than 60 s is not necessary in our scenarios.

Currently, opening windows are the recommended practice to reduce the risk of virus spread in an enclosed environment (WHO, 2020). Our study shows that in certain cases an opened window in a multi-room environment is likely to spread particles faster than when windows are closed. We suggest that the window should be closed when the door to the room is open. This lowers the potential risk of spreading a virus or indoor contaminants, potentially causing adverse health and irritation effects.

CRediT authorship contribution statement

M.R.R.S. van Beest: Conceiving and planning the research, Designing the theoretical experiment, Performing the actual CFD calculations, Processing the CFD data, Writing – original draft, Writing – review & editing. F. Arpino: Designing the theoretical experiment, Performing the actual calculations, Processing the CFD data, Writing – original draft, Writing – review & editing. O. Hlinka: Performing the actual CFD calculations. E. Sauret: Designing the theoretical experiment, Writing – review & editing. N.R.T.P. van Beest: Processing the CFD data. R.S. Humphries: Writing – review & editing. G. Buonanno: Writing – review & editing. L. Morawska: Conceiving and planning the research, Designing the theoretical experiment, Writing – review & editing. G. Governori: Conceiving and planning the research, Writing – review & editing. N. Motta: Conceiving and planning the research, Writing – review & editing.

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.

Acknowledgements

This project was supported by resources and expertise provided by CSIRO IMT Scientific Computing for the assistance in running the OpenFOAM CFD simulations on the Pearcely Super Computer in an efficient manner. The authors confirm that no funding was received for this work. The authors declare that there are no competing interests.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apr.2022.101473.

References

AGIHI, Hygienists and others, 2009. Documentation of the threshold limit values and biological exposure indices. In: Chest. AGIHI, pp. 74–75. Ahmadzadeh, M., Farahki, E., Shams, M., 2021. Investigating the effect of air conditioning on the distribution and transmission of COVID-19 virus particles. J. Cleaner Prod. 128147. Ahmadzadeh, M., Shams, M., 2021. Passenger exposure to respiratory aerosols in a train cabin: Effects of window, injection source, output flow location. Sustainable Cities Soc. 75, 103280. Aissa, A., Abdelouahab, M., Noureddine, A., Elganaoui, M., Pateyron, B., 2015. Ranz and marshall correlations limits on heat flow between a sphere and its surrounding gas at high temperature. Therm. Sci. 19 (5), 1521–1528. Argyropoulos, C.D., Markaton, N., 2015. Recent advances on the numerical modelling of turbulent flows. Appl. Math. Model. 39 (2), 603–732. Arpino, F., Cortellina, G., Dell’Isola, M., Massarotti, N., Masuro, A., 2014. High order explicit solutions for the transient natural convection of incompressible fluids in tall cavities. Num. Heat Transfer Part A. Appl. 66 (8), 839–862. Berglund, B., Brunekreef, B., Knappe, H., Lindvall, T., Maroni, M., Mathie, L., Skov, P., 1992. Effects of indoor air pollution on human health. Indoor Air 2 (1), 2–25. Blachere, S.M., Linsey, W.G., Pearce, T.A., Anderson, S.E., Fisher, M., Khakoo, R., Meade, B.J., Lander, O., Davis, S., Thewlis, R.E., et al., 2009. Measurement of airborne influenza virus in a hospital emergency department. Clin. Infect. Dis. 48 (4), 438–440. Bourouiba, L., Dehandschoewercker, E., Bush, J.W., 2014. Violent expiratory events: on coughing and sneezing. J. Fluid Mech. 745, 537–563. Burki, T., 2020. Prisons are “in no way equipped” to deal with COVID-19. Lancet (London, England) 395 (10234), 1411. Carnevali, C., Torresan, S., Simonato, L., Scappellato, M., Tassari, R., Visentin, A., Lotti, M., Mannarelli, P., 2010. Carbon monoxide pollution is associated with decreased lung function in asthmatic adults. Eur. Respir. J. 35 (2), 266–272. Charter, Y., Pessa-Silva, C., 2009. Natural ventilation for infection control in health-care settings. World Health Organization. Cortellina, G., Stabile, L., Arpino, F., Faleiros, D., Van Den Bos, W., Morawska, L., Buonanno, G., 2021. Close proximity risk assessment for SARS-CoV-2 infection. Sci. Total Environ. 794, 148749. Cowan, J.M., Burris, J.M., Hughes, J.R., Cunningham, M.P., 2010. The relationship of normal body temperature, end-expired breath temperature, and BAC/BrCa ratio in 48 profoundly fit human test subjects. J. Anal. Toxicol. 34 (5), 238–242. Crowe, C.T., Schwarzkopf, J.D., Sommersfeld, M., Tuji, Y., 2011. Multiphase flows with droplets and droplet clusters. CRC Press. Dubou, T., Drickakis, D., 2021. On airborne virus transmission in elevators and confined spaces. Phys. Fluids 33 (1), 011905. Dietz, L., Horve, P.F., Cole, D.A., Fretz, M., Eisen, J.A., Van Deymen, E., 2020. 2019 Novel coronavirus (COVID-19) pandemic: Built environment considerations to reduce transmission. Msystems 5 (2). Effros, R.M., Hoagland, K.W., Bosbous, M., Castillo, D., Foss, B., Dunning, M., Garre, L., Lin, W., Sun, F., 2002. Dilution of respiratory solutes in exhaled condensates. Am. J. Respir. Crit. Care Med. 165 (3), 63–69. Fabini, P., Brah, J., Houseman, E.A., Gern, J., Milton, D.K., 2011. Origin of exhaled breath particles from healthy and human rhinovirus-infected subjects. J. Aerosol Med. Pulmon. Drug Deliv. 24 (3), 137–147. Gan, W.H., Lim, J.W., David, K., 2020. Preventing intra-hospital infection and transmission of COVID-19 in healthcare workers. Saf. Health At Work. Gendarmes, F., 2015. Methods of detection and characterization. In: Nanoengineering. Elsevier, pp. 55–84. Jamriska, M., Morawska, L., 2003. Quantitative assessment of the effect of surface deposition and coagulation on the dynamics of submicrometer particles indoors. Aerosol Sci. Technol. 37 (5), 425–436. Jo, S., Hong, J., Lee, S.-E., Ki, M., Choi, B.Y., Sung, M., 2019. Airflow analysis of Pyeongtaek St Mary’s hospital during hospitalization of the first middle east respiratory syndrome patient in Korea. R. Soc. Open Sci. 6 (3), 181164. Johnson, G., Morawska, L., Ristovski, Z., Hargreaves, M., Mengersen, K., Chao, C.Y.H., Wan, M., Li, Y., Xie, X., Katochnikv, D., et al., 2011. Modality of human expired aerosol size distributions. J. Aerosol Sci. 42 (2), 839–851. Kulkarni, H., Smith, C.M., Lee, D.D.H., Hirst, R.A., Easton, A.J., O’Callaghan, C., 2016. Evidence of respiratory syncytial virus spread by aerosol. Time to revisit infection control strategies? Am. J. Respir. Crit. Care Med. 194 (3), 308–316. Liu, S., 2021. Mystery of the seventh floor - how did the virus spread in hotel quarantine. In: Brisbane Times. https://www.brisbanetimes.com.au/national/ queensland/mystery-of-the-seventh-floor-how-did-the-virus-spread-in-hotel-quarantine-20210113-p5651.html Web-page (Accessed 21 Jan 2021). Li, Y., Qian, H., Hang, J., Chen, X., Hong, L., Liang, L., Pi, J., Xiao, S., Wei, J., Liu, L., et al., 2020a. Evidence for probable aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant. Cold Spring Harbor Laboratory Press, MedRiv. Li, H., Zhong, K., Zhai, Z.J., 2020b. Investigating the influences of ventilation on the fate of particles generated by patient and medical staff in operating room. Build. Environ. 107038. Liao, Y., Lucas, D., 2018. Evaluation of interfacial heat transfer models for flashing flow with two-fluid CFD. Fluids 3 (2), 38.
Lindsley, W.G., Pearce, T.A., Hudnall, J.B., Davis, K.A., Davis, S.M., Fisher, M.A., Khakoo, R., Palmer, J.E., Clark, K.E., Celik, I., et al., 2012. Quantity and size distribution of cough-generated aerosol particles produced by influenza patients during and after illness. J. Occup. Environ. Hyg. 9 (7), 443–449.

Massarotti, N., Arpino, F., Lewis, R., Nithiarasu, P., 2006. Explicit and semi-implicit CBS procedures for incompressible viscous flows. Internat. J. Numer. Methods Engrg. 66 (10), 1618–1640.

McFall-Ngheim, M., 2020. How the ‘failed’ quarantine of the diamond princess cruise ship started with 10 coronavirus cases and ended with more than 700. https://www.businessinsider.com.au/how-diamond-princess-cruise-ship-coronavirus-quake-wrong-2020-2?r=US&IR=T Web-page (Accessed 25 Feb 2020).

Mizumoto, K., Kagaya, K., Zarebski, A., Chowell, G., 2020. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the diamond princess cruise ship, Yokohama, Japan, 2020. Eurosurveillance 25 (10), 2000180.

Morawska, L., Cao, J., 2020. Airborne transmission of SARS-CoV-2: The world should face the reality. Environ. Int. 105730.

Morawska, L., Tang, J.W., Bahneth, W., Blyssen, P.M., Boestra, A., Buonanno, G., Cao, J., Dancer, S., Floto, A., Franchimon, F., et al., 2020. How can airborne transmission of SARS-CoV-2 indoors be minimised? Environ. Int. 142, 105832.

Nicas, M., Nazaroff, W.W., Hubbard, A., 2005. Toward understanding the risk of secondary airborne infection: emission of respirable pathogens. J. Occup. Environ. Hyg. 2 (3), 143–154.

Nothing, L., 2021. Queensland records no new COVID-19 cases overnight as genome sequencing confirms source of yesterday’s infection. In: ABC. https://www.abc.net.au/news/2021-07-27/covid-qld-zero-cases-genome-sequencing-hotel-quarantine/100321162?utm_campaign=news-article-share-control&utm_medium=content_shared&utm_source=abc_news_web Web-page (Accessed 27 July 2021).

Open Cascade, 2005-2021. Salome: The open source integration platform for numerical simulations. https://www.salome-platform.org/ Web-page (Accessed 01 Nov 2021).

OpenCFD Ltd., 2021. OpenFOAM: Open source CFD software. https://www.openfoam.com/ Web-page (Accessed 01 Nov 2021).

O’rourke, P., 1980. Modelling of drop interactions in thick sprays and a comparison with experiments. I. Mech. E., C 404 (80), 101–116.

Princess Cruise Line, 2022. Diamond princess deck plan. https://www.princess.com/diamond-princess-deck-plan Web-page (Accessed 10 Jan 2022).

Qian, H., Zheng, X., 2018. Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings. J. Thoracic Dis 10 (Suppl 19), S2295.

Rocklöv, J., Sjödin, H., Wilder-Smith, A., 2020. Simulation of aerosol transmission on a boeing 737 airplane with intervention measures for COVID-19 mitigation. Phys. Fluids 33 (3), 033112.

Tang, J., Eames, I., Li, Y., Taha, Y., Wilson, P., Bellingan, G., Ward, K., Breuer, J., 2005. Door-opening motion can potentially lead to a transient breakdown in negative-pressure isolation conditions: the importance of vorticity and buoyancy airflow. J. Hosp. Infect. 61 (4), 283–286.

Tang, J., Li, Y., Eames, I., Chan, P., Ridgway, G., 2006. Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. J. Hosp. Infect. 64 (2), 100–114.

Tang, J.W., Nicolle, A.D., Klettner, C.A., Pantelic, J., Wang, L., Suheimi, A.B., Tan, A.Y., Ong, G.W., Su, R., Sekhar, C., et al., 2013. Airflow dynamics of human jets: sneezing and breathing-potential sources of infectious aerosols. PLoS One 8 (4), e59970.

Tang, J.W., Nicolle, A., Pantelic, J., Koh, G.C., De Wang, L., Amin, M., Klettner, C.A., Cheong, D.K., Sekhar, C., Tham, K.W., 2012. Airflow dynamics of coughing in healthy human volunteers by shadowgraph imaging: an aid to aerosol infection control. PLoS One 7 (4), e34818.

Taylor, J., 2021. Family of three contract covid from infected neighbours in hotel quarantine in Sydney. In: The Guardian. https://www.theguardian.com.australia-news/2021/apr/18/family-of-three-contract-covid-from-infected-neighbours-in-hotel-quarantine-in-sydney Web-page (Accessed 22 July 2021).

University of Maine Ocean Observing System (UMOOS), 2021. Beaufort wind scale. http://gyre.umeoce.maine.edu/data/gomoos/buoy/php/variable_description. php?variable=wind_2_speed Web-page (Accessed 01 Nov 2021).

Versteeg, H.K., Malalasekera, W., 2007. An Introduction to Computational Fluid Dynamics: The Finite Volume Method. Pearson education.

Vuorinen, V., Aarnio, M., Alava, M., Alopeux, V., Atanasova, N., Auvinen, M., Balasubramanian, N., Bordbar, H., Erästö, P., Grande, R., et al., 2020. Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors. Saf. Sci. 104866.

Wang, Z., Galea, E.B., Grandison, A., Ever, J., Jia, F., 2022. A coupled computational fluid dynamics and Wells-Riley model to predict COVID-19 infection probability for passengers on long-distance trains. Saf. Sci. 147, 105572.

WHO, 2020. Coronavirus disease (COVID-19) advice for the public. https://www.who.int/mediacentre/factsheets/19-qld-zero-cases-genome-sequencing-hotel-quarantine-in-sydney Web-page (Accessed 22 July 2021).

Wilson, J., 2006. Infection Control in Clinical Practice. Elsevier Health Sciences.

Yang, S., Lee, G.W., Chen, C.-M., Wu, C.-C., Yu, K.-P., 2020. Transmission potential and severity of COVID-19 in South Korea. Int. J. Infect. Dis.

Spengler, J.D., Sexton, K., 1983. Indoor air pollution: a public health perspective. Science 221 (4605), 9–17.

Standards Australia, 2012. AS 1668.2-2012, The use of ventilation and airconditioning in buildings Part 2: Mechanical ventilation in buildings. SAI Global Limited under license from Standards Australia Limited, British-Standard-Institution: ISBN: 9781743422984.

Talan, K., Abuhegazy, M., Mahfouz, O.A., Anderoglu, O., Poroseva, S.V., 2021. Simulation of aerosol transmission on a boeing 737 airplane with intervention measures for COVID-19 mitigation. Phys. Fluids 33 (3), 033112.

Shim, E., Tariq, A., Choi, W., Lee, Y., Chowell, G., 2020. Transmission potential and severity of COVID-19 in South Korea. Int. J. Infect. Dis.