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ABSTRACT

In this paper, we investigate the aerosol cloud flow physics during three respiratory actions by humans (such as coughing, talking, and breathing). With given variables (i.e., velocity, duration, particle size and number of particles, and ambient conditions), the standoff safe distance during coughing, talking, and breathing should be the distance where virus-laden droplets and aerosols do not have significant transmission to another person. However, at a critical distance, the aerosol cloud flux can still be extremely high, which can immediately raise the transmission in a localized area to another person during a static condition. In this study, computational fluid dynamics analysis of selective respiratory actions has been carried out to investigate the effect of the standoff distance and assess the importance of social distancing in indoor places. The prediction of the aerosol transport due to flow generated from coughing, talking, and breathing was obtained by applying the Eulerian–Lagrangian approach. From the simulation results, it can be concluded that the aerosols released due to continuous talking travel a similar distance to that released due to sudden coughing. On the other hand, aerosols exhaled from breathing do not travel a long distance but float in air for a long time.

I. INTRODUCTION

Droplets ejected from an asymptomatic host are one of the biggest risks during the current coronavirus (COVID-19) pandemic in the transmission of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Although stringent measures such as lockdown have reduced the spread of the virus and the public places are gradually opening, social distancing will be followed for the foreseeable future and the risks of transmission will not be reduced until a large section of population is vaccinated. Understanding the transmission of the virus will require a thorough understanding of the flow physics of droplets and aerosols. The flow physics of droplets and aerosols depends on many complex parameters, such as differences in expiratory flows during sneezing, coughing, talking, and breathing (different velocities and duration, droplet size distribution, number, and temperature), ambient conditions [ambient mean and turbulent velocity, temperature, and relative humidity (RH)], and physical phenomenon (droplet collisions, breakdown-coalescence, and evaporation–condensation). Experimental or numerical modeling of the flow dynamics of droplets and aerosols transport from expiratory flows will provide the quantitative data for developing guidelines for social distancing in various indoor and outdoor settings. As advised through fundamental assessments based on fluid dynamics (Mittal *et al.*, 2020), the COVID-19 pandemic has pushed the scientific community and attracted new studies to be undertaken to understand critical scientific challenges, such as respiratory droplet formation, two-phase expiratory flows, droplet evaporation and transport, and associated aerodynamics [Feng *et al.* (2020) and Xu *et al.* (2017)].

The respiratory actions, such as coughing, sneezing, talking, breathing, or other mixed types, release a large number of droplets into the atmosphere. Wells (1934) showed that the fate of these expiratory droplets depend on the dynamics of inertia, gravity, and evaporation. Droplets larger than a critical size drop to the ground faster than they evaporate, while the droplets smaller than the critical size evaporate before they reach the ground, forming droplet nuclei (aerosols). The transmission of respiratory viruses including COVID-19 between humans occurs via three routes: (i) direct impact of large droplets on the face, nose, and eye of a recipient from a virus-laden respiratory flow ejected with sufficient momentum, (ii) touching the surface contaminated by the deposition of large droplets and subsequent transfer to respiratory mucosa, and (iii) inhalation of air carrying droplet nuclei (aerosols; Mittal *et al.*, 2020). The first two routes are known as "large droplet" transmission, while the third route is known as airborne transmission [Mittal *et al.* (2020) and Morawska (2006)]. It was advised during the early stages of the COVID-19 pandemic that there is an urgent need to acknowledge the airborne spread of the SARS-CoV-2 virus [Kumar and Morawska (2019) and Morawska and Cao (2020)]. The World Health Organization (WHO) now believes (WHO, 2020a and 2020b) that the ongoing pandemic with the SARS-CoV-2 virus is airborne, and the transmission of such a virus is via aerosols. Airborne transmission is defined as the spread of an infectious agent caused by the dissemination of droplet nuclei (aerosols) that remain infectious when suspended in air over long distances and time (WHO, 2014). In this research, we investigate the transport of aerosol cloud during three respiratory actions by humans (such as coughing, talking, and breathing).

The initial guideline on a social distancing of 2 m (NHS, 2020), 1.83 m (CDC, 2020), or 1 m (WHO, 2020a; 2020b) is based on the disease transmission theory originally developed in the 1930s based on a simplified physics of a single droplet evaporation and fall-off by Wells (1934). Xie *et al.* (2007) revaluated the Wells evaporation-falling curve by solving heat and mass transfer as well as a transport equation for a single droplet and reported that for respiratory exhalation flows, the sizes of the largest droplets that would totally evaporate before falling a 2 m distance are between 60 μm and 100 μm, and these expelled large droplets are carried to more than 6 m distance by exhaled air at a velocity of 50 m/s (sneezing), more than 2 m distance at a velocity of 10 m/s (coughing), and less than 1 m distance at a velocity of 1 m/s (breathing). Bourouiba *et al.* (2014) argued that violent expiratory flows due to coughing and sneezing should be considered as two-phase flows of droplets within a warm air cloud. Based on the experimental data using non-evaporative beads, their developed empirical model predicted a fallout distance of 0.5 m for 700 μm droplets and 2.4 m for 30 μm droplets from coughing. Balachandar *et al.* (2020) further treated expiratory flow as the droplet movement within a puff of cloud and developed an analytical model to study the concentration and droplet size distribution due to evaporation. Their results show that while the larger droplets of more than 100 μm fall off from the cloud rapidly and the smaller droplets of less than 1 μm evaporate quickly into residues, the intermediate size droplets between 1 and 100 μm still undergo evaporation after 1.5 s. However, what is unknown from their study is how far the cloud containing evaporating droplets will travel.

Recently, Computational Fluid Dynamics (CFD) played a significant role in providing the answer to how far droplets can travel. Dbouk and Drakakis (2020a) have simulated two-phase droplet transport considering the most realistic flow physics of exhaled droplet size distribution, droplet mass transfer and its evaporation, surrounding environment temperature, and relative humidity. There simulations show that droplets fall to the ground at around 1 m distance from the source due to coughing at 20 °C temperature and 50% relative humidity (RH) within a stationary ambient environment but travel to more than 6 m under an ambient airflow velocity of more than 4 km/h. Vuorinen *et al.* (2020) in their recent computational fluid dynamics (CFD) simulations of aerosol transport in relation to SARS-CoV-2 transmission gave various examples on the transport and dilution of aerosols (d $\leqslant$ 20 μm) over distances (10 m) around supermarket shelves. They also accounted the locally varying aerosol concentration levels that a susceptible can inhale. Interestingly, they introduced the concept of "exposure time" to virus containing aerosols to complement the traditional "safety distance" thinking. It was shown that the exposure time to inhale 100 aerosol droplets could range from 1 s to 1 min or even to 1 h depending on the situation. Their modeling considered the aerosol to be made of 10 μm droplets as well as massless droplets and both considerations produced similar results.

Wang *et al.* (2020b) used an Eulerian–Lagrangian particle tracking model to investigate the evaporation of various droplet sizes under different temperature and relative humidity conditions for free-falling droplets and continuous and pulsating cough jets with no ambient flow as well as upward and downward ambient flows of 0.1 m/s without ambient turbulence. Their simulation shows that the 100 μm droplet can have a 50% probability of traveling to 1.0 m at 20 °C at both 50% and 100% relative humidity (RH), while 50 μm droplets can have a 50% probability of traveling up to 2.8 m and 3.2 m at the relative humidity of 50% and 100%, respectively. Furthermore, their simulations show that the droplets remain airborne between 10 s and 20 s under different ambient conditions. Pendar and Páscoa (2020) have reported the transport of saliva droplets in the indoor environment using the Eulerian–Lagrangian particle tracking model. They have simulated a number of practical scenarios such as standing near a table, standing face-to-face, wearing mask, and different head tilting positions. Their focus was on the transport of large droplets during sneezing. Their simulation showed that the droplet with a mean droplet size of 90 μm can travel up to 2.3 m and the droplet with a mean droplet size of 540 μm droplets can travel more than 4 m. Another interesting finding from their study is that bending the head downward during sneezing can reduce the droplet traveling distance by more than 22%.

Droplet transport due to sneezing has been reported by Busco *et al.* (2020), considering the biomechanics of a person during sneezing using motion capture and applying CFD modeling for different angular head positions. The conventional straight head modeling shows that the droplets can travel to 4 m during sneezing while considering head motion and time-varying air-expiration, and the simulation produces a droplet transport distance of 3 m. Wang *et al.* (2020a) presented droplet motion of various sizes from coughing through experimentation and CFD modeling. They have considered the evaporation of droplets in their modeling and their study shows that the largest droplet of 800 μm can travel 1.8 m. Li *et al.* (2020) investigated the droplet transport between two persons standing at 1 m and 2 m distances during coughing under ambient outdoor conditions under different relative humidity and air velocities. Their simulation shows that under a wind speed of 2 m/s, smaller droplets expired from coughing can deposit on the face of a person standing at 2 m. Considering fluid dynamics and human physiology factors driving droplet dispersion from a human sneeze, Fontes *et al.* (2020) suggested that the resulting exposure levels are highly dependent on the fluid dynamics that can vary depending on several human factors. For example, a sneeze without flow in the nasal passage (consistent with congestion) yields a 300% rise in the droplet content at 1.83 m (≈6 ft) and an increase over 60% on the spray distance 5 s after the sneeze. Dbouk and Drikakis (2021) investigated the aerosol transport inside an elevator due to a mild cough. They employed the Eulerian–Lagrangian technique with heat transfer, droplet evaporation, and droplet–droplet interactions. Their study shows that the placements of inlets and outlets inside the elevator have significant effects on ambient flow dynamics and thus on aerosol dispersion. The position of the subject inside the elevator also significantly influences the dispersion. The presence of an air purifier fails to eliminate droplet dispersion. Nazari *et al.* (2021) investigated aerosols transport due to a sneeze within an underground car park under the influence of jet fans. They have employed the Eulerian–Lagrangian particle tracking method with the aerosol cloud represented by a fixed droplet size of 3.5 μm. Their simulation shows that the use of jet fans disperses aerosol over a large area of the car park. Their simulation shows that the spaces near the fresh air duct could be a safe zone. Zhang *et al.* (2021) investigated aerosol transport inside a bus under its heating, ventilation, and air conditioning (HVAC) conditions as well as opened and closed window conditions using experiment and CFD modeling. In the experiment, they have used a smoke generator to distribute aerosol, and in the CFD simulation, they have used the Eulerian–Eulerian modeling with the aerosols treated as a passive scalar. Their study concludes that although the HVAC system carries the aerosol from an infected person to a susceptible person within 1 min, the HVAC system dilutes the aerosol concentration and thus reduces the inhalation risk over a short period of time. Opening windows also reduces the overall concentration of aerosol but increases the concentration near the opened window and thus increases the risk to those seating near the opened window. Abuhegazy *et al.* (2020) have investigated aerosol transport within a classroom and investigated the effects of glass barriers and windows opening for aerosol transport. They have used the Eulerian–Lagrangian droplet transport with fixed droplet sizes. Their simulation shows that the glass barriers and opened window can significantly reduce the aerosol concentration within the classroom.

It is now established that a significant spread of COVID-19 happens from asymptomatic people indoors (Leclerc *et al.*, 2020), and by definition, an asymptomatic person does not cough or sneeze; rather, the expiratory flows are caused by talking and breathing (Asadi *et al.*, 2020). Stelzer-Braid *et al.* (2009) performed experiments with patients suffering from cold by collecting exhaled aerosols during breathing, coughing, and talking and comparing with the positive nasal mucous sample. Their study confirms that breathing and talking leads to the expiration of virus-laden aerosols. Stadnytskyi *et al.* (2020) used the laser scattering to analyze speech droplets generated during a continuous talking of 25 s. From analyzing the droplet sizes, they estimated that 1 min of loud talking can generate 1000 virion-containing droplet nuclei that remain airborne for more than 8 min. However, their modeling ignored the droplet–droplet and droplet–airflow interactions. Morawska *et al.* (2009) have established that the vocalization can emit one order of magnitude more particle than breathing and Asadi *et al.* (2019) identified that certain individuals are "speech super emitters" who can emit up to 10 droplets/s and estimated that a 10-min conversion with an infected asymptomatic super emitter talking at a normal volume can expose the conversational partner or someone at close proximity to an invisible cloud of 6000 aerosols droplets. The peak exhaled air velocity is 1–3 m/s (Tang *et al.*, 2013) during quiet breathing and 2–5 m/s during talking (Xu *et al.*, 2017), and these airflows can carry exhaled droplets and aerosols quite a long distance. Unlike coughing and sneezing conditions, the distance traveled by aerosols due to talking and breathing has not been investigated extensively.

The focus of the present study is on the transport of the aerosol cloud during talking and breathing (likely because of the release of virus-laden droplets from an asymptomatic infected person) and comparing the transport against that from coughing. Over the long run, the research will investigate the understanding of mechanisms of droplet size distribution, droplet evaporation, and droplet nuclei and aerosol formation, and transport. However, in this paper, we implement a simplified modeling approximation to represent aerosol cloud transport during three respiratory actions by humans (such as coughing, talking, and breathing) in the computational fluid dynamics (CFD) simulations.

II. METHODOLOGY

OpenFOAM®, an open-source software for computational fluid dynamics (CFD) simulations, was employed in simulating the respiratory actions by humans (such as coughing, talking, and breathing plume). The spreading and dissipation of the aerosol cloud in air are modeled via the Eulerian–Lagrangian approach, as this approach deals with individual particles and calculates the trajectory of each particle separately. The large number of released particles by respiratory action are necessary to obtain an appropriate description of expiratory flows. For the bulk carrier fluid of air, we have employed Reynolds-Averaged Navier–Stokes (RANS) equations with the standard $k-\varepsilon$ turbulence model. The detailed description of these equations can be found in many textbooks, including that of Versteeg and Malalasekera (2007).

In the Eulerian–Lagrangian concept, while the airflow is solved on an Eulerian fixed mesh, all particles are treated as discrete particles, where the location and velocity of each particle are traced through the Eulerian mesh using integrated Newton's second law of motion. In the present study, Multi-Phase Particle-In-Cell (MPPIC) modeling, i.e., MPPICFoam solver of OpenFOAM, was used, where particle–particle collisions were included in the modeling through calculating stresses from a particle pressure gradient within each control volume rather than resolving each individual collision, as described in the work of Snider (2001). The Ergun/Wen–Yu model is used within the MPPICFoam solver and the Ergun/Wen–Yu model considers the effect of the cluster of droplets. For higher air volume fractions, the Wen–Yu model (1966) is used, and for a lower air volume fraction, the Ergun equation (1952) is used. In this modeling approach, the interphase momentum exchange between the air and droplets phases is provided through the drag coefficient as follows:

Interphase momentum exchange coefficient,

$$K_{lg} = \frac{3}{4} C_D \frac{\alpha_l \alpha_g \rho_g |\vec{v}_l - \vec{v}_g|}{d_p} \alpha_g^{-2.65} \quad \text{for} \quad \alpha_g > 0.8, \qquad (1)$$

TABLE I. Simulation variables.

Actions	Velocity (m/s)	Duration (s)	Particle size (microns)	No. of particles	Reference
Coughing	10	0.3	1, 5, 10	1005 in 0.3 s	Dbouk and Drikakis (2020a); Xie *et al.* (2007)
Talking	5	Continuous	1, 10	10 in 1 s	Xie *et al.* (2007); Asadi *et al.* (2019)
Breathing	1	Continuous	1	2 in 1 s	Xie *et al.* (2007); Asadi *et al.* (2019)
Density of saliva (water) = 1000 kg/m^3 Density of air = 1.18 kg/m^3 Conditions = 20 °C, 50% RH					Bourouiba *et al.* (2014)

$$K_{lg} = 150\frac{\alpha_l(1-\alpha_g)\mu_g}{\alpha_g d_p^2} + 1.75\frac{\alpha_l\rho_g|\vec{v}_l - \vec{v}_g|}{d_p} \quad \text{for} \quad \alpha_g \le 0.8, \tag{2}$$

where

$$C_D = \frac{24}{\alpha_g Re_p}\left[1 + 0.15(\alpha_g Re_p)^{0.87}\right] \quad \text{for} \quad Re_p < 1000,$$
$$C_D = 0.44 \quad \text{for} \quad Re_p \ge 1\,000, \tag{3}$$

and

$$Re_p = \frac{\rho_g d_p|\vec{V}_l - \vec{V}_g|}{\mu_g}, \tag{4}$$

where α_l is the droplet volume fraction, α_g is the air volume fraction, ρ_g is the density of air, μ_g is the viscosity of air, d_p is the diameter of droplets, v_l is the velocity of droplets, and v_g is the velocity of air.

Expiratory events of coughing, talking, and breathing release a wide range of droplets [O(0.1 μm)–O(1000 μm), Mittal *et al.*, 2020] and their size changes within the flow due to evaporation. Instead of using a particle size distribution and modeling the evaluation of particle sizes due to evaporation, we have used the fixed particle sizes of 1, 5, and 10 μm to capture the aerosol cloud transport. Previous studies (Balachandar *et al.*, 2020 and Mittal *et al.*, 2020) show that larger droplets evaporate into submicron to 10 μm in size. These small droplets remain suspended and transported in air currents and are the cause of airborne transmission. In the present study, the location of these droplets within the air jet where they are evaporated into droplet nuclei has not been modeled, and treating all the particles with a constant diameter at the source will not capture the initial event of droplets dynamics. However, the spreading and dissipation of resulting exhaled aerosol cloud occur over a much longer time period compared to the rapid release of mass and momentum of the exhaled air during coughing, breathing, and talking, and it is assumed that the actual resolution of the initial event is not critically important for simulating aerosol transport (Vuorinen *et al.*, 2020). Vuorinen *et al.* (2020) concluded by comparing the spreading and decay of aerosol cloud represented by fixed 10 μm and 20 μm that the cough-released aerosol cloud spreading and decay can be adequately predicted by any particle sizes of 10 μm and below as well, treating the aerosol cloud as massless particles. Similarly, a fixed droplet size of 1 μm has been used in predicting the aerosol transport in a classroom relevant to COVID-19 (Abuhegazy *et al.*, 2020), and a fixed droplet size of 3.5 μm was used for simulating aerosol transport in a car park (Nazari *et al.*, 2021). In the present simulations, the human mouth print was represented by a rectangle with a length of 4 cm and a height of 0.484 cm according to the human mouth photograph captured during coughing by Dbouk and Drikakis (2020b), and the saliva droplet laden airflow was released at an assumed mouth height of 1.6 m according to a representative human height. Table I gives simulation variables used in the present study.

Figure 1 shows a cross-sectional view of the computational mesh used in the present study. The computational domain is three dimensional with a length of 4 m, a height of 2 m, and a width of 1 m. The mesh was concentrated around the mouth print. The total number of hexahedral cells used in the simulations were 253 748. Hexahedral meshing was deployed as it generates meshes composed of deformed cubes (hexahedra) and it can significantly improve both speed and accuracy. The geometry and mesh were created using the open-source SALOME software. This software provides a generic platform for pre- and post-processing for the numerical simulation. An extensive mesh independency test was carried out by comparing the velocity and pressure along the length of the air jet for successive mesh refinement, and 253 748 hexahedral cells have been found to produce mesh independent results.

We employed different inlet velocities and durations depending on the expiratory events as the inlet condition. For a single cough, we set the inlet air and droplet injection velocity of 10 m/s over 0.3 s and then set both the inlet and injection velocities to zero. We also simulated three consecutive coughs, setting the inlet velocity of 10 m/s over 0.3 s and then reducing the inlet velocity to 1 m/s representing breathing over 0.2 s and repeating the process for three cycles. For continuous talking and breathing cases, we kept the steady inlet conditions throughout the duration of simulations. The simulations were carried out in transient manner with a time step of 2×10^{-4} s. We employed the UK National Supercomputing Service ARCHER using 96 core parallel processing for the simulations.

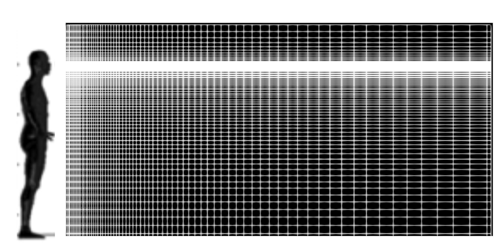

FIG. 1. Schematic of the computational mesh shown in 2D (note that the human figure is for demonstration only).

III. RESULTS AND DISCUSSION

A. Saliva aerosol travel from a single cough

As reviewed by Xu *et al.* (2017), the long-distance saliva aerosol transport is highly environment dependent. While the large droplets can fall off from the expiratory jet, small droplets of less than 100 μm usually evaporate into smaller droplets of submicron to 10 μm to form aerosol (Mittal *et al.*, 2020). In the present study, the transport of aerosol has been simulated using 10, 5, and 1 μm droplets, and it was assumed that the aerosol was generated at the source. (Vuorinen *et al.*, 2020) explained that the actual resolution of the initial event is not critically important for simulating aerosol transport as the spreading and dissipation of aerosol occur over a much longer time scale compared to the initial expiratory events.

Figure 2 (Multimedia view) and Fig. 3 show the development of airflow as well as the saliva aerosol trajectory from a single cough at 10 m/s over 0.3 s.

After 0.3 s, the airflow velocity was set to zero without any droplet injection. The carrier airflow creates a jet flow until 0.3 s, and after 0.3 s, the jet dissipates quickly once the mouth is closed. The simulation shows that droplet transport is almost identical for three droplet sizes. This is because the droplets smaller than 10 μm do not influence the aerosol simulation patterns, as the effects of gravity and inertia of individual droplets become negligible and the aerosol transport is influenced by mainly by the ambient flow physics and

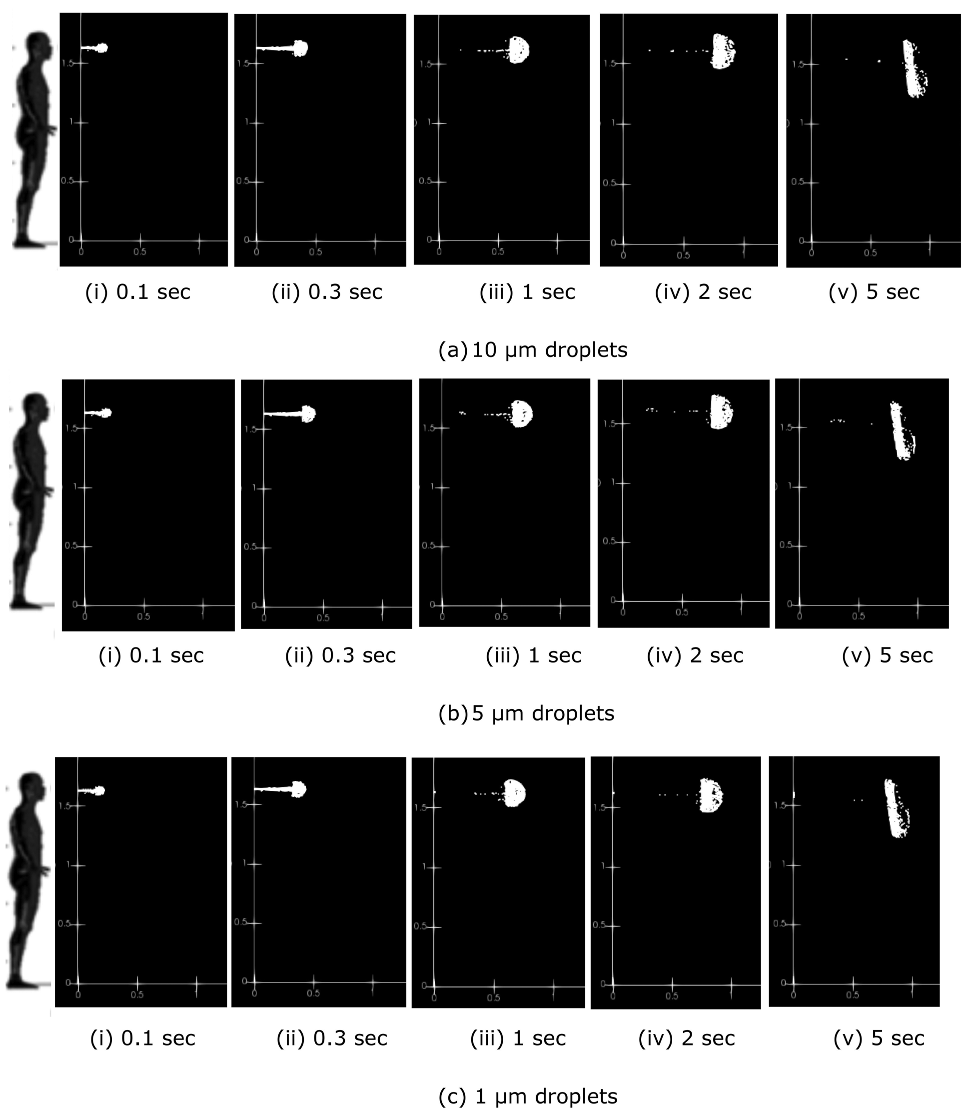

FIG. 2. Saliva aerosol trajectories from a single cough: (a) 10 μm droplets, (b) 5 μm droplets, and (c) 1 μm droplets. Multimedia view: https://doi.org/10.1063/5.0042952.1

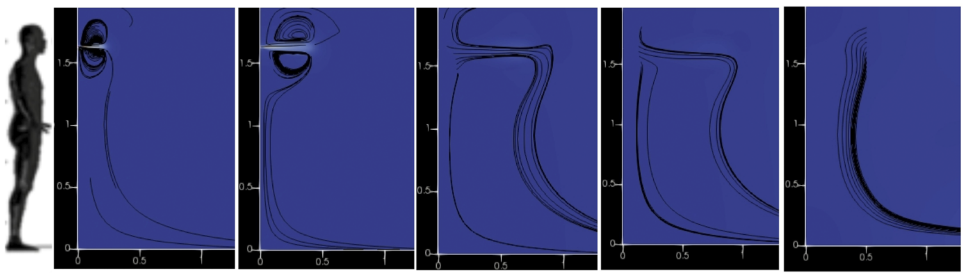

FIG. 3. Air velocity in the longitudinal direction from a single cough with streamlines.

turbulence. The ejected droplets from the mouth are seen to form a mushroom cloud structure. The mushroom cloud is formed by vortices at the edge of the jet boundary and turbulence dispersion (see Fig. 3). Once the mouth is closed after 0.3 s, the mushroom detaches itself from the mouth, loses its momentum, and grows in sizes due to the entrainment of the surrounding air into the cloud and turbulence dispersion. The width of the cloud is much larger than the width of the air jet. At around 5 s, the initial momentum from the coughing is completely lost, with the cloud structure starting to fall toward the ground driven by the ambient flow structure (see Fig. 3 for streamline). Under the initial momentum generated by the cough, the aerosol cloud travels to 1.01 m before starting downward flow. Despite using a simplified modeling approach to represent aerosol cloud, our simulation results reproduced the same 1 m distance traveled by a single cough cloud, as reported by Dbouk and Drikakis (2020b).

B. Saliva aerosol travel from three coughs and continuous breathing

For this case of simulation, the inlet velocity was set at 10 m/s for 0.3 s representing coughing and set at by 1 m/s representing breathing for 0.2 s. This cycle was repeated three times, and after that, the inlet air velocity was kept at 1 m/s over the duration of the simulation. Droplets were released during coughing only. The simulation was carried out with 10 μm droplets. Figure 4 (Multimedia view) and Fig. 5 show the droplet trajectory and air velocity contour and streamlines, respectively.

The intermittent nature of the carrier airflow is clearly visible between 1.0 and 2.0 s velocity plot. A single larger jet is formed after 2 s and that remains visible at 5.0 s. Droplets released from three coughs ultimately merge into a single larger mushroom cloud of droplets. The distance traveled by the cloud of droplets is ~1.2 m. The cloud is not sustained by the continuous breathing flow and starts to fall after 5.0 s. It is interesting to note that the continuous coughing and breathing do not lead to a significant increase in the distance traveled by aerosol cloud compared to that from a single cough.

C. Saliva aerosol travel from continuous talking

Figure 6 (Multimedia view) and Fig. 7 show the trajectory of droplets and carrier airflow velocity and streamlines from the continuous talking with the air and droplet velocity set at 5 m/s throughout the duration of the simulation.

We have simulated the aerosol trajectory with both 1 μm and 10 μm droplets and simulation results show that both droplet sizes produce almost similar results, as shown in Fig. 6. In stationary air, the terminal velocity for a 10 μm water droplet is 2.868 mm/s, while for a 1 μm water droplet, the terminal velocity is 0.028 68 mm/s, which indicates that a 10 μm droplet will take 9 min to settle to the ground, while a 1 μm droplet will take 15.5 h. However, expiratory

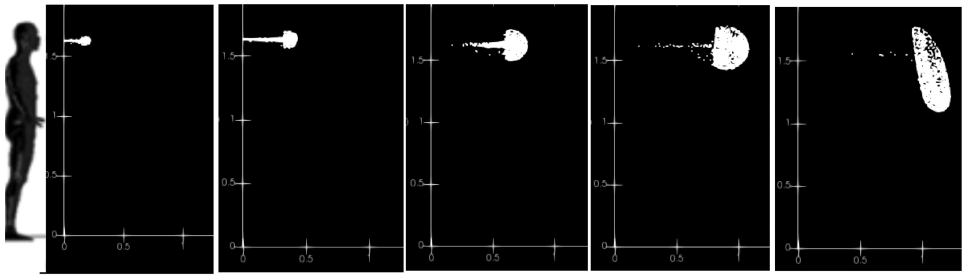

FIG. 4. Saliva aerosol transports due to continuous coughing and breathing. Multimedia view: https://doi.org/10.1063/5.0042952.2

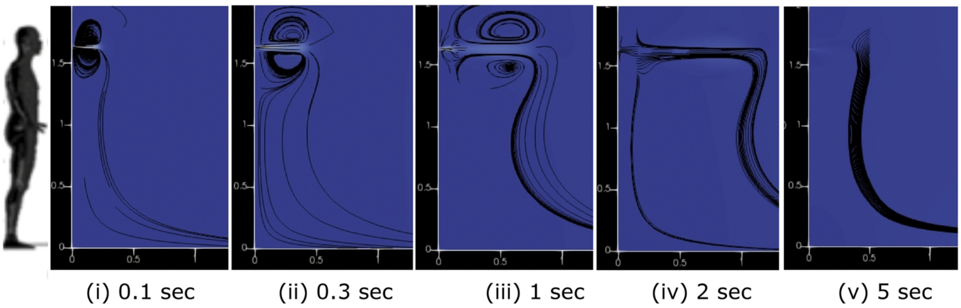

FIG. 5. Air velocity in the longitudinal direction for continuous coughing and breathing with streamlines.

events create small and large vortices in ambient air and the droplet trajectory is driven by the ambient airflow and turbulence resulting in very similar fall-off for both 10 and 1 μm droplet aerosol clouds. Bourouiba (2020) argued that instead of considering the individual droplet fall off in stationary air to explain large and small droplets transport, droplets transport from expiratory events of coughing and sneezing should be modeled as a multiphase turbulent gas cloud that entrains ambient air and carries within it clusters of droplets. Figure 7 shows that a stable jet is established after 5 s due to continuous talking with the jet reaching an ~1.0 m distance. Since the number of droplets released during talking is low (ten droplets/s) and the flow is continuous, a mushroom cloud was not observed and the aerosol trajectory forms a classic parabolic shape. The distance traveled by the aerosol cloud is ~1.0 m.

D. Saliva aerosol travel from continuous breathing

Figure 8 (Multimedia view) and Fig. 9 show that the particle trajectories and carrier airflow velocity during continuous breathing with the air and droplet velocities were set at 1 m/s. We have simulated the aerosol cloud trajectory with 1 μm droplets. In this case, two droplets were released from the mouth per second. The simulation results show that droplets can travel ~0.3 m under a steady state air jet flow established at 5.0 s. Since the number of droplets ejected

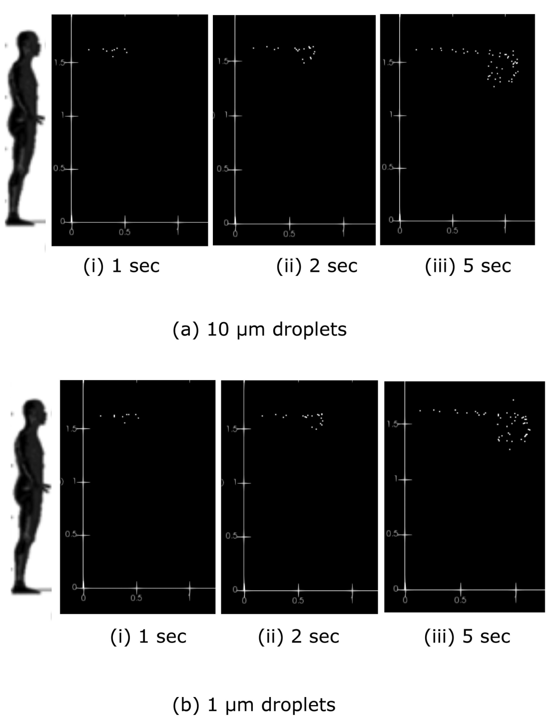

FIG. 6. Saliva aerosol transport during continuous talking: (a) 10 μm droplets and (b) 1 μm droplets. Multimedia view: https://doi.org/10.1063/5.0042952.3

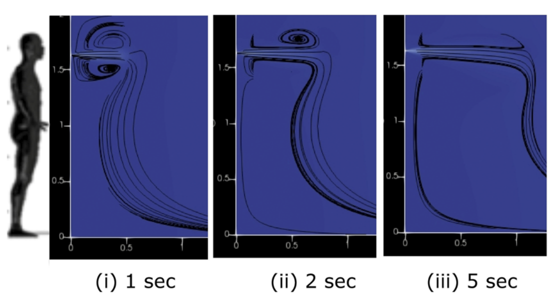

FIG. 7. Air velocity during continuous talking with streamlines.

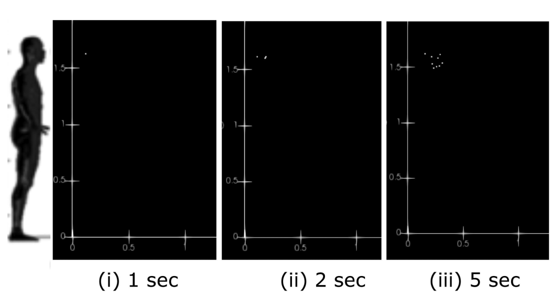

FIG. 8. Saliva aerosol transport for breathing. Multimedia view: https://doi.org/10.1063/5.0042952.4

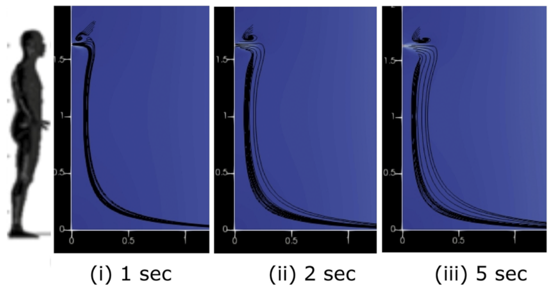

FIG. 9. Air velocity during breathing with streamlines.

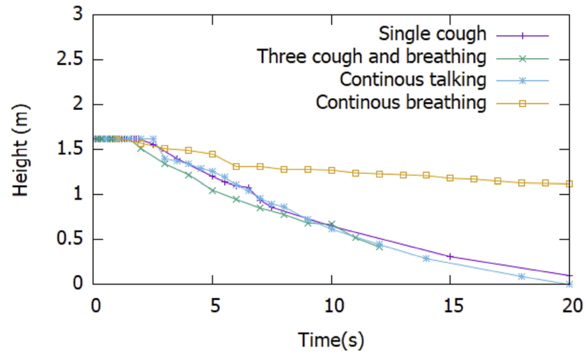

FIG. 11. Fall rate of aerosol cloud.

is low, droplets are dispersed and travel without much interaction with each other in a classic parabolic direction.

E. Quantitative analyses

One of the key quantification parameters is how far the droplets and aerosol cloud can travel. Figure 10 shows the horizontal distance traveled by the front of the aerosol cloud during coughing, talking, and breathing with different simulation conditions. Figure 10 shows that the droplet travel distance does not exceed the safe social distance of 2 m. As presented earlier, after 5 s, the droplet cloud start to disperse and starts to fall downward under the ambient vortices and turbulence. The results clearly show that the droplets ejected during continuous talking can easily reach ∼ 1 m, and thus, continuous talking of an infected person can pose a substantial transmission risk.

The second parameter that quantifies the risk of transmission is how long the droplets linger in air before falling to the ground. Figure 11 shows the falling rate of droplets and clouds under different expiratory conditions. Except for the breathing condition, the aerosol cloud drops to a human waist level within ∼12 s. Only few droplets are released during breathing and individual droplets do not form a cloud and thus drop slowly, while aerosol cloud drops faster to the ground from coughing and talking due to vortex wake behind droplets accelerating downward flow. Using a different modeling concept for treating aerosol cloud, Dbouk and Drikakis (2020a)

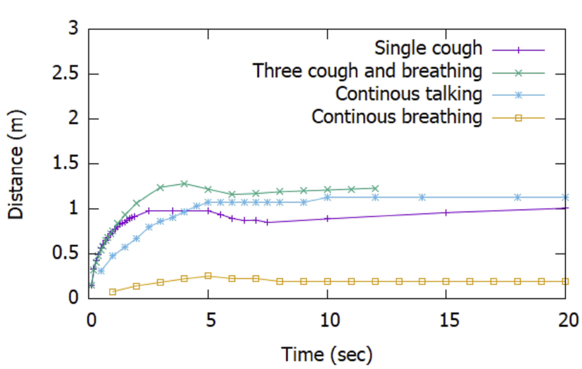

FIG. 10. Aerosol cloud penetration distance.

predicted that the time for the fall of droplet to the waist level is ∼15 s.

As demonstrated above that the aerosol transport due to coughing and that due to talking are of similar characteristics, an asymptomatic person talking continuously to a nearby person poses sufficient risk of airborne transmission. While coughing releases more droplets compared to talking and breathing, continuous nature of talking and breathing over a prolonged time can lead to a large amount of aerosol droplet transport, therefore underlying the importance of social distancing measures for everyone, especially avoiding busy paths or places and preparing to slow down or stop to help keep distance.

Overall, our present work shows insight into how far the aerosol droplet cloud can travel from coughing, talking, and breathing as well as the falling rate of aerosol cloud for different expiratory conditions.

IV. CONCLUSIONS AND RECOMMENDATIONS

In this paper, we investigated aerosol transport during three respiratory actions by humans (such as coughing, talking, and breathing) and analyzed aerosol cloud aerodynamics. For the simulations, we have utilized the Eulerian–Lagrangian particle tracking with the standard $k - \varepsilon$ model for treating turbulence. The MPPIC solver of OpenFOAM has been used in simulation, which considers collisions between droplets. From the simulation results, the following conclusions can be made:

- Our model-based prediction indicates that the aerosol cloud travels ∼1 m during coughing and talking and less than 0.2 m during breathing.
- Without the surrounding wind speeds, the aerosol cloud drops to the ground within 15–20 s and below the human waist level in ∼12 s. Thus, these aerosols may not constitute a risk regarding facial contact of adults if they move into space left by an infected asymptomatic person after ∼12 s.
- The droplets from coughing create a mushroom cloud structure whose size is larger than the initial jet diameter and can disperse over a larger area under the ambient air velocity or the ventilation system.

The simulation results show that the aerosol cloud does not travel beyond the social distancing guideline of 2 m. However, physical distancing is not always feasible in many settings such as in airplanes or pubs. It is also not possible to wear masks while eating in a restaurant. This guidance can be improved and tailored to specific environment, deepening our understanding of airborne transmission due to the interaction between exhalation and inhalation airflows. Both exhalation and inhalation airflows are affected by the thermal plume generated by people with different postures and gestures. We need further research to establish the risk of transmission between two people as well as among a group of people considering human posture and gesture and relative positions and orientations. Understanding the flow physics of aerosol transport and the associated models can be used to develop multi-layered guidelines that differentiate between individual and group interactions at different settings.

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The authors report no conflict of interests.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Abuhegazy, M., Talaat, K., Anderoglu, O., and Poroseva, S. V., "Numerical investigation of aerosol transport in a classroom with relevance to COVID-19," Phys. Fluids **32**, 103311 (2020).

Asadi, S., Bouvier, N., Wexler, A. S., and Ristenpart, W. D., "The coronavirus pandemic and aerosols: Does COVID-19 transmit via expiratory particles?," Aerosol Sci. Technol. **54**(6), 635–638 (2020).

Asadi, S., Wexler, A. S., Cappa, C. D., Barreda, S., Bouvier, N. M., and Ristenpart, W. D., "Aerosol emission and superemission during human speech increase with voice loudness," Sci. Rep. **9**(1), 2348 (2019).

Balachandar, S., Zaleski, S., Soldati, A., Ahmadi, G., and Bourouiba, L., "Host to host transmission as a multiphase flow problem for science based social distance guidelines," Int. J. Multiphase Flows **132**, 103439 (2020).

Bourouiba, L., "Turbulent gas clouds and respiratory pathogen emissions potential implications for reducing transmission of COVID-19," Clin. Rev. Educ. **323**(18), 1837–1838 (2020).

Bourouiba, L., Dehandschoewercker, E., and Bush, J. W. M., "Violent expiratory events: On coughing and sneezing," J. Fluid Mech. **745**, 537–563 (2014).

Busco, G., Yang, S. R., Seo, J., Hassan, Y. A., and Hassan Y. A., "Sneezing and asymptomatic virus transmission," Phys. Fluids **32**, 073309 (2020).

CDC, How to Protect Yourself and Others. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/prevention.html; accessed December 16, 2020.

Dbouk, T. and Drikakis, D., "On coughing and airborne droplet transmission to humans," Phys. Fluids **32**, 053310 (2020a).

Dbouk, T. and Drikakis, D., "On respiratory droplets and face masks," Phys. Fluids **32**, 063303 (2020b).

Dbouk, T. and Drikakis, D., "On airborne virus transmission in elevators and confined spaces," Phys. Fluids **33**, 011905 (2021).

Ergun S., "Fluid flow through packed columns," Chem. Eng. Prog. **48**, 89–94 (1952).

Feng, Y., Marchal, T., Sperry, T., and Yi, H., "Influence of wind and relative humidity on the social distancing effectiveness to prevent COVID-19 airborne transmission: A numerical study," J. Aerosol Sci. **147**, 105585 (2020).

Fontes, D., Reyes, J., Ahmed, K., and Kinzel, M., "A study of fluid dynamics and human physiology factors driving droplet dispersion from a human sneeze," Phys. Fluids **32**, 111904 (2020).

Kumar, P. and Morawska, L., "Could fighting airborne transmission be the next line of defence against COVID-19 spread?," City Environ. Interact. **4**, 100033 (2019).

Leclerc, Q. J., Fuller, N. M., Knight L. E., Funk, S., and Knight, G. M., "What settings have been linked to SARS-CoV-2 transmission clusters?," Wellcome Open Res. **5**(83), 83 (2020).

Li, H., Leong, F. Y., Xu, G., Ge, Z., Kang C. W., and Lim K. H., "Dispersion of evaporating cough droplets in tropical outdoor environment," Phys. Fluids **32**, 113301 (2020).

Mittal, R., Ni, R., and Seo, J.-H., "The flow physics of COVID-19," J. Fluid Mech. **894**, F2-1–F2-13 (2020).

Morawska, L., "Droplet fate in indoor environments, or can we prevent the spread of infection?," Indoor Air **16**, 335–347 (2006).

Morawska, L. and Cao, J., "Airborne transmission of SARS-CoV-2: The world should face the reality," Environ. Int. **139**, 105730 (2020).

Morawska, L., Johnson, G. R., Ristovski, Z. D., Hargreaves, M., Mengersen, K., Corbett, S., Chao, C. Y. H., Li, Y., and Katoshevski, D., "Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities," J. Aerosol Sci. **40**(3), 256–69 (2009).

NHS, Coronavirus (COVID-19) https://www.gov.uk/coronavirus?gclid=Cj0KCQjw59n8BRD2ARIsAAmgPmLg4CKu91HItyeba0YGO3VR6MnaADvAIyiOHOM-xOVWCizQk8xqZIgaApemEALw_wcB; accessed on December 16, 2020.

Nazari, A., Jafari, M., Rezaei, N., Taghizadeh-Hesary, F., and Taghizadeh-Hesary, F., "Jet fans in the underground car parking areas and virus transmission," Phys. Fluids **33**, 013603 (2021).

Pendar, M.-R. and Páscoa, J. C., "Numerical modeling of the distribution of virus carrying saliva droplets during sneeze and cough," Phys. Fluids **32**, 083305 (2020).

Snider, D. M., "An incompressible three-dimensional multiphase particle-in-cell model for dense particle flows," J. Comput. Phys. **170**, 523–549 (2001).

Stadnytskyi, V., Bax, C. E., Bax, A., and Anfinrud, P., "The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission," Proc. Natl. Acad. Sci. U. S. A. **117**(22), 11875–11877 (2020).

Stelzer-Braid, S., Oliver, B. G., Oliver, B. G., Blazey, A. J., Argent, E., Newsome, T. P., Rawlinson, W. D., and Tovey E. R., "Exhalation of respiratory viruses by breathing, coughing and talking," J. Med. Virol. **81**, 1674–1679 (2009).

Tang, J. W., Nicolle, A. D., Klettner, C. A., Pantelic, J., Wang, L., Suhaimi, A. B., Tan, A. Y. L., Ong, G. W. X., Su, R., Sekhar, C., Cheong, D. D. W., and Tham, K. W., "Airflow dynamics of human jets: Sneezing and breathing-potential sources of infectious aerosols," PLoS One **8**, e59970 (2013).

Vetsteeg, H. and Malalasekera, W., *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*, 2nd ed. (Pearson, 2007).

Vuorinen, V., Aarnio, M., Alava, M., Alopaeus, V., Atanasova, N., Auvinen, M., Balasubramanian, N., Bordbar, H., Erästö, P., Grande, R., Hayward, N., Hellsten, A., Hostikka, S., Hokkanen, J., Kaario, O., Karvinen, A., Kivistö, I., Korhonen, M., Kosonen, R., Kuusela, J., Lestinen, S., Laurila, E., Nieminen, H. J., Peltonen, P., Pokki, J., Puisto, A., Råback, P., Salmenjoki, H., Sironen, T., and Österberg, M., "Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors," Safety Sci. **130**, 104866 (2020).

Wang, B., Wu, H., and Wan, X.-F., "Transport and fate of human expiratory droplets—a modeling approach," Phys. Fluids **32**, 083307 (2020a).

Wang, H., Li, Z., Zhang, X., Zhu, L., Liu, Y., and Wang, S., "The motion of respiratory droplets produced by coughing," Phys. Fluids **32**, 125102 (2020b).

Wells, W. F., "On air-borne infections: Study II. Droplets and droplet nuclei," Am. J. Epidemiol. **20**(3), 611–618 (1934).

Wen, C.Y. and Yu, Y.H., "Mechanics of fluidization," Chem. Eng. Prog. Symp. Ser. **62**, 100–111 (1966).

WHO, Infection Prevention and Control of Epidemic-and Pandemic-Prone Acute Respiratory Infections in Health Care. Geneva: World Health Organization; 2014, available at https://apps.who.int/iris/bitstream/handle/10665/112656/9789241507134_eng.pdf;jsessionid=41AA684FB64571CE8D8A453C4F2B2096?sequence=1; accessed August 19, 2020.

WHO, Coronavirus Disease (COVID-19) Advice for the Public https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public; accessed December 16, 2020a.

WHO, Scientific Brief Transmission of SARS-CoV-2: Implications for Infection Prevention Precautions, 2020b available at https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions; accessed August 19, 2020.

Xie, X., Li, Y., Chwang, A. T. Y., Ho, P. L., and Seto, W. H., "How far droplets can move in indoor environments—Revisiting the Wells evaporation–falling curve," Indoor Air **17**, 211–225 (2007).

Xu C., Nielsen, P. V., Liu, L., Jensen, R. L., and Gong, G., "Human exhalation characterization with the aid of schlieren imaging technique," Build. Environ. **112**, 190–199 (2017).

Xu, R., Cui, B., Duan, X., Zhang, P., Zhou, X., and Yuan, Q., "Saliva: Potential diagnostic value and transmission of 2019-nCoV," Int. J. Oral Sci. **12**, 11 (2020).

Zhang, Z., Han, T., Yoo, K. H., Capecelatro, J., Boehman, A. L., and Maki, K., "Disease transmission through expiratory aerosols on an urban bus," Phys. Fluids **33**, 015116 (2021).