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Effects of High-speed Wind, Humidity, and Temperature on the Generation of a SARS-CoV-2 Aerosol; a Novel Point of View

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ABSTRACT

The new coronavirus (SARS-CoV-2) is rapidly spreading across communities around the world. Respiratory droplet transmission is a common transmission route for many airborne diseases, including novel coronavirus disease (COVID-19). Wearing the face mask prevents respiratory droplet transmission. Both face mask leakage and non-use of the face mask under high-speed wind conditions can increase the risk of SARS-CoV-2 transmission. The respiratory droplets' behavior during sneezing or coughing (i.e., the size and the distance between droplets) depends on face mask wearing. The respiratory droplets during coughing and sneezing break apart into extremely small respiratory droplets (i.e., cloud of aerosol) upon interaction with the high-speed wind condition. The volume-of-fluid (VOF) method has been used to study the deformation and breakup of a single respiratory droplet placed in high-speed wind flow in the presence of smaller neighboring respiratory droplets. The effect of the diameter of respiratory droplets and the distance between them on the breakup mechanism has been investigated using open-source field operation and manipulation (OpenFOAM) libraries. The results are presented for the dimensionless distance and the normalized diameter of the secondary respiratory droplet in the ranges of 2 to 6 and 0.4 to 0.8, respectively. According to the results of simulations, the spreading of SARS-CoV-2 increases with a decrease in respiratory droplet breakup time. In addition, the effects of ambient relative humidity and temperature on the cloud of respiratory particles were analyzed.

Keywords: COVID-19, SARS-CoV-2, Dynamic of respiratory droplets, VOF, OpenFOAM, Aerosol of viruses, Deformation and breakup, Ambient condition

1 INTRODUCTION

Since December 2019, novel coronavirus disease (COVID-19) has become a major concern for the global population. It has led to 915,393 deaths worldwide as of September 12, 2020 (Johns Hopkins University and Medicine, 2020). It simulated the clinical course of infection with two previously reported human coronaviruses—including severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV) which was named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) by the Coronavirus Study Group of the International Committee on Taxonomy of Viruses (Zhu *et al.*, 2020). Various studies have

reported that severe acute SARS-CoV-2 spreads mainly through respiratory droplets and aerosols (Yan *et al.*, 2018; Asadi *et al.*, 2019; Hsiao *et al.*, 2020; National Academies of Sciences, 2020; Riediker and Morawska, 2020; Wilson *et al.*, 2020). Respiratory droplets can transmit SARS-CoV-2 through the air (Xie *et al.*, 2009; Rezaei *et al.*, 2020; Nazari *et al.*, 2021). These respiratory droplets can be exhaled during coughing, sneezing, or even talking (Xie *et al.*, 2009). The World Health Organization (WHO) defined droplets as particles $\geq 5\text{--}10\text{ }\mu\text{m}$ in diameter and aerosols as particles $< 5\text{ }\mu\text{m}$ (Wilson *et al.*, 2020). Under high-speed wind conditions, respiratory droplets may convert to very small respiratory droplets in the wind direction. In this situation, the risk of SARS-CoV-2 transmission increases. Additionally, the deformation and breakup of respiratory droplets under wind conditions play a key role in the spread of new coronaviruses. Under high-speed wind conditions, the change in behavior of the respiratory droplets (i.e., their number and size) significantly increases the risk of SARS-CoV-2 transmission. Furthermore, based on the source of respiratory droplets and face mask wearing, different sizes of droplets (such as large ones and aerosols)—which behave differently in the outdoor environment—can be generated. Researchers have been seeking various solutions on how to control SARS-CoV-2 from spreading into communities (Ameri *et al.*, 2020a, b; Bhardwaj and Agrawal, 2020; Li *et al.*, 2020; Plog *et al.*, 2020; Rakhsha *et al.*, 2020; Siavashpour *et al.*, 2020; Taghizadeh-Hesary and Akbari, 2020; Wang *et al.*, 2020).

Dbouk and Drikakis (2020a) numerically studied airborne droplet transmission during coughing. They found that respiratory droplets could travel unexpected considerable distances depending on the high-speed wind conditions. Dbouk and Drikakis (2020b) demonstrated that respiratory droplets from coughing or sneezing traveled a distance less than 2 m in the case of zero-wind conditions. Bourouiba (2020) found that expelled respiratory droplets during human sneezing could travel up to 7–8 m at 36–108 km h⁻¹ wind speeds. Chaudhuri *et al.* (2020) presented a model for the early phases of a COVID-19-like pandemic based on the aerodynamics and evaporation characteristics of respiratory droplets. They recognized that respiratory droplets exclusively contribute to the infection growth rate, which depends on the ambient temperature and relative humidity. Various researchers recommended the use of face masks in the public environment, and some of them believed that social distancing of 2 m may not be adequate during the COVID-19 outbreak (Schroter, 2020).

Dbouk and Drikakis (2020a) investigated the temporal behavior of respiratory droplet–droplet interactions on the high-speed wind. They found that respiratory droplet breakup occurs at different rates depending on environmental conditions, such as wind speed. In this work, the advanced stages of the breakup of the resulting respiratory particle clouds were observed, and a clear definition and quantification of the respiratory droplet breakup times were offered.

A comprehensive review of COVID-19 transmission via respiratory droplets was conducted by Carelli (2020), Chen (2020), Chen *et al.* (2020), and Drossinos and Stilianakis (2020). The infection probabilities of COVID-19 via large respiratory droplets were analyzed by Sun and Zhai (2020). They found 1.6–3.0 m as a safe social distance.

A better understanding of how respiratory droplets deform and break-up on high-speed wind may provide insight that contributes to mitigating SARS-CoV-2 spread. The influence of high-speed wind, relative humidity, and temperature on the respiratory droplets break-up (i.e., evaporation) is a complex topic. In this study, we introduce a novel numerical solution for heat and mass transfer for respiratory droplet interactions, which provide generated aerosol as a function of high-speed wind, relative humidity, and ambient temperature, as well as including virus fluid properties. To the best of our knowledge, the problem of deformation and interaction of multiple respiratory droplets in the high-speed wind flows has not been investigated in previous literature. The main aim of our work is to present predictions of the flow behavior and regimes resulting from the collision, deformation, and fragmentation of two and three respiratory droplets placed in a high-speed wind flow. This helps investigators gain a deep understanding of the behavior of complex wind flows, which are engaged with the dynamics of respiratory droplets. Then, different breakup regimes, including the stripping breakup regime, have been introduced. The simulations were carried out at a high-speed wind of 50 km h⁻¹ with various configurations of the respiratory droplets, including different positions and diameters of the neighboring respiratory droplets.

The rest of the paper is arranged as follows. Section *governing equation* presents details of the mathematical modeling, the dimensionless numbers, and assumptions. The section *Problem description and numerical technique* discusses the details of the geometry, the description of the

case studies, and the details of the numerical technique. After validation of our results using existing experimental and numerical data in the sections *Validation of Results* and *Results and discussion* presents a comprehensive discussion of the results and some advice. Finally, a conclusion is provided.

2 GOVERNING EQUATION

The relevant equations of motion are the momentum conservation law, the continuity equation, the energy equation, and the phase fraction equation in their incompressible form, respectively represented as:

$$\rho \frac{DU}{Dt} = -\nabla P + \int_{S(t)} \sigma \kappa (x') n(x') \delta(x - x') dS + \nabla \cdot \tau [0, 1] \quad (1)$$

$$\nabla \cdot (\rho U) = 0 \quad (2)$$

$$\rho C \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + \frac{1}{2} \tau : (\nabla U + \nabla U^T) \quad (3)$$

$$\frac{\partial \rho_k \alpha_k}{\partial t} + \nabla \cdot (\rho_k U_k \alpha_k) = 0 \quad (4)$$

where p , σ , τ are the pressure, the surface tension coefficient, and the deviatoric stress tensor, respectively. *Stokes'* hypothesis and the symmetry of the stress tensor are supposed to be valid. The surface force acting at the liquid-gas interface is considered by the surface integral in Eq. (1). κ is twice the mean curvature of the interface, and n is the unit normal vector of the interface. $\delta(x - x')$ denotes the *Dirac-delta* function, $x' \in S(t)$ is a point on the interface and x is the point at which the equation is evaluated (Tryggvason *et al.*, 2001). In Eq. (3), $E = \rho e + 1/2 \rho U^2$ is the total energy per unit volume, with e being the internal energy per unit mass of the fluid and ρ being the density.

Eq. (4) is provided by the volume-of-fluid (VOF) model, which governs the volume fraction α of one fluid in the mixture. The VOF method determines a phase fraction (α) for each cell within the computational domain. The cells having α equal to 1 and 0 contain only water and gas phases, respectively (Berberović *et al.*, 2009).

In Eq. (3), the viscous dissipation term has been neglected. The effect of gravity is small for the corresponding size and lifetime of the respiratory droplets. For a given length scale D , three-time scales of advection, surface tension, and viscous effects exist. Based on these scales, the *non-dimensional Reynolds number* and the *Weber number* can be obtained as follows.

$$Re = \frac{\rho_g u_g D}{\mu_g}, \quad We = \frac{\rho_g u_g^2 D}{\sigma} \quad (5)$$

The characteristic parameters are the initial respiratory droplet diameter D_0 , the gas velocity u_g , the inlet gas pressure p_g , the water density ρ_l , and the gas density at the inlet ρ_g .

$$t^* = t \frac{u_g}{D_0} \sqrt{\frac{\rho_g}{\rho_l}}, \quad l^* = \frac{l}{D_0}, \quad d^* = \frac{d}{D_0}, \quad (6)$$

where t^* denotes the dimensionless time (Simpkins and Bales, 1972; Guildenbecher *et al.*, 2009), x^* , u^* , and a^* are the dimensionless position, velocity, and acceleration, respectively. l^* and d^* are the normalized distance and diameter of the secondary respiratory droplet, respectively.

The high-speed turbulent effects are modeled using the Reynolds-averaged form of Eqs. (1)–(4) are called the Reynolds-averaged Navier–Stokes equations (or RANS equations) along with

Table 1. Physical properties of water and air at the STP condition.

	ρ (kg m ⁻³)	μ (Pa.s $\times 10^{-3}$)	σ (N m ⁻¹)
Air	1.21	0.018 (Xie <i>et al.</i> , 2007)	-
Water	977 (Chaudhuri <i>et al.</i> , 2020)	1.1	0.0657 (Zhang <i>et al.</i> , 2011)

the standard k - ϵ turbulence model to address the closure problem. The initial values of the turbulent kinetic energy and the turbulent dissipation rate are 0.735 m² S⁻² and 3.835 m² S⁻³, respectively (Smits and Dussauge, 2006; Rodrigues *et al.*, 2016). For the complete description of the respiratory droplet-droplet collision, it is necessary to consider the physical properties involving viscosity, density, and surface tension coefficient at the standard condition. These parameters are listed in Table 1. It is well documented in the literature that average human respiratory droplets during sneezing and coughing consist of water, salt, proteins, and virus (SARS-CoV-2)/bacteria (Xie *et al.*, 2007; Zhang *et al.*, 2011; Chaudhuri *et al.*, 2020).

3 PROBLEM DESCRIPTION AND NUMERICAL TECHNIQUE

Figs. 1 and 2 represent the schematic view of respiratory droplet ejection during a human cough or sneeze with or without wearing a face mask, respectively. The diameter and distance of the expelled respiratory droplets depend on the usage of the face mask. Given that larger and closer respiratory droplets can be expelled without wearing masks, the effects of the diameter and distance between the respiratory droplet on the breakup time, the catch-up time, and the collision morphology have been studied. Larger respiratory droplets may carry SARS-CoV-2 and thus constitute more danger in terms of COVID-19 transmission under high-speed wind conditions.

The open-source field operation and manipulation (OpenFOAM) CFD software package version 4.1 was used to perform the numerical simulations. The OpenFOAM codes were written in C++ programming language using the finite-volume numerical technique to solve the conservation of mass, energy, and momentum along with the equation of state in their Reynolds-averaged form. The base code of our solver is *compressibleInterFoam* (Deshpande *et al.*, 2012; OpenFOAM Foundation Ltd., 2016a, b). This solver can take into account different equations of state (EOS) models, but the stiffened-gas EOS is not included by default. Therefore, this feature is added to the basic codes by changing the source codes.

The second-order upwind scheme was used to handle the convective terms except for the phase-fraction term, which was discretized using the Van-Leer second-order scheme. The Gauss-linear second-order approach was employed to address the diffusion terms. The *PISO*

Fig. 1. Schematic view of respiratory droplet dispersion from a human cough or sneeze with a mask wearing at a high-speed wind of 50 km h⁻¹.

Fig. 2. Schematic view of respiratory droplet dispersion from a human cough or sneeze without mask wearing at a high-speed wind of 50 km h^{-1} .

algorithm was applied to couple the pressure and the velocity. The under-relaxation factors for the pressure, momentum, and energy equations were 0.4, 0.8, and 0.9, respectively. In addition, the minimum residuals for convergence of pressure, velocity, and temperature were 10^{-7} , 10^{-6} , and 10^{-8} , respectively.

Fig. 3 represents the schematic view of the computational domain, including the inlet and boundary conditions and the topology of the computational grid. To generate an effective computational mesh, we have used the *block-mesh utility*. The numerical mesh structure was gradually refined from the outer boundary with a cell size of $D_0/h = 3$ towards the surface of the respiratory droplets ($D_0/h = 24$) by halving the size of the cells, in which h is the cell size. The dimensions of the entire computational domain were $6D_0$ and $22.5D_0$ in the radial and streamwise directions, respectively. It is found that these sizes are large enough to guarantee that the results are not affected by the dimensions of the domain.

The fixed-value and fixed-flux pressure conditions are imposed at the inlet. The outlet-inlet is employed to model the outlet and far-field boundaries. The main respiratory droplet was supposed to be initially at rest and spherical with the diameter of $D_0 = 300 \text{ }\mu\text{m}$ placed at the distance $7.5D_0$ from the inlet. The distance between the secondary nonidentical respiratory droplets and the main respiratory droplet in the tandem arrangement was $l^* = 2\text{--}6$.

4 VALIDATION OF RESULTS

The comparison of our data with the experimental visualizations presented by Xie *et al.* (2007) for the two-dimensional numerical simulation of the morphology for the spherical water droplet is illustrated in Fig. 4. The airflow with a fixed magnitude moved over the respiratory droplet. The respiratory droplet temperature was set to 20°C , and the ambient pressure, p_∞ , was 105 kPa. The drop reached the minimum pressure of 100 Pa at the leeward side. Fig. 4 demonstrates the comparison of the temporal droplet diameter between the present work and those of Xie *et al.* (2007). The maximum relative deviation of the droplet diameter for the two cases in Fig. 4 was approximately 3%.

The *grid independence test* was carried out to compute the required number of numerical cells to obtain convergent results. To obtain the grid-independent results, simulations have been carried out on three different mesh topologies at the high-speed wind of 50 km h^{-1} past a single spherical respiratory droplet. Fig. 5 presents the VOF contours using the three mentioned numerical coarse, fine, and finest meshes. Three computational meshes were generated with the following details: A = 1500, B = 2000, and C = 2500. Grids B and C produce almost identical results for the VOF contours with a relative error of less than 0.3%. Hence, numerical grid B chose to have a

Fig. 3. Schematic two-dimensional (axisymmetric) view of the computational domain including the boundary conditions for the case of breakup of the respiratory droplet in high-speed wind flow.

Fig. 4. Comparison of the temporal variation of the droplet diameter with the results of Xie *et al.* (2007).

Fig. 5. The VOF contours around a single respiratory droplet obtained using (a) coarse mesh A, (b) fine mesh B, and (c) finest mesh C.

convergent solution with the optimized computational cost. A summary of the output of the grid independence test is shown in Fig. 5. The maximum skewness of the grid was 0.3, which is quite suitable to obtain accurate results. The number of grid points over the smallest respiratory droplet in the finest mesh was 150. The numerical predictions were also analyzed concerning the size of the time step. Therefore, three different time steps were considered, and the VOF contours were computed, yielding the results that prove that the time-step size-independent results have been obtained using the nondimensional time-step size of 0.02. It should be noted that the time steps have been normalized by the inlet flow velocity and the main respiratory droplet diameter, $(\Delta t u_g)/D_0$.

5 RESULTS AND DISCUSSION

The present paper focuses on the morphology of a single respiratory droplet placed in a high-speed wind flow in the presence of small neighboring respiratory droplets. We assume that the secondary respiratory droplet can move with the high-speed wind flow and impact the main respiratory droplet. The dimensionless distance between two respiratory droplets was 2, 3, 4, 5, and 6. The normalized diameters of the small respiratory droplets were 0.8, 0.6, and 0.4. Due to the presence of other respiratory droplets inside the domain, the breakup process for the main respiratory droplet includes collision with the secondary respiratory droplet, penetration into the respiratory droplet, and splashing of the respiratory droplet. In addition, the effects of wind velocity, relative humidity, and ambient temperature have been studied. We defined the cloud of airborne to study the effect of the abovementioned parameters on the viruses, airborne, and very small respiratory droplets spreading during coughing and sneezing. Fig. 6 demonstrates the cloud of the created aerosol after the main respiratory droplet splashing. Three- and two-respiratory droplets before the collision and the cloud of the airborne and viruses after respiratory droplet splashing are shown schematically in Fig. 7.

5.1 CASE A: INTERACTION OF TWO RESPIRATORY DROPLETS

5.1.1 Stage 1- Penetration

Figs. 8 and 9 ($t^* = 0.01$ – 0.3) present the time-elapsing images of the two-dimensional respiratory droplet deformation. The normalized diameter of the first respiratory droplet in two cases is 0.4

Fig. 6. View of the cloud of the airborne and the width of aerosol during the splashing of the main respiratory droplets.

Fig. 7. Schematic view of the respiratory droplets cloud from a human cough or sneeze without mask wearing.

and 0.6, and the dimensionless distance between the two droplets is equal to 2, 3, 4, 5, and 6. At this stage, the smaller respiratory droplet moves with the velocity of the upstream flow and then strikes the main respiratory droplet. As the secondary respiratory droplet touches the main respiratory droplet, a liquid film starts to spread in the outward direction. A corona (in this case, is not the new coronavirus/SARS-CoV-2) around the secondary respiratory droplet is formed, which grows over time as the smaller respiratory droplet continues to feed the liquid film. Hence, the diameter of the liquid disk is greater in the case of the impact of the larger respiratory droplet. With continuous penetration of the smaller respiratory droplet into the main respiratory droplet, several coronas become visible on the frame, indicating that the timescale of the formation of the corona is much larger than the timescale of the deformation of the main respiratory droplet.

The comparison of the contours presented in Figs. 8 and 10 reveals that with increasing diameter of the secondary respiratory droplet, the time of penetration of the second respiratory droplet into the main respiratory droplet decreases. Clearly, when the larger respiratory droplet collides with the main respiratory droplet, the diameter of the created hole is larger in comparison

Fig. 8. Two-dimensional view of the two-respiratory droplet deformation at the penetrating and splashing stages. The dimensionless distance between the respiratory droplets is 2 (the first column), 3 (the second column), and 4 (the third column). The normalized diameter of the second respiratory droplet for the specified dimensionless distance is 0.4.

Fig. 9. Two-dimensional view of the two-respiratory droplet deformation at the penetrating and splashing stages. The dimensionless distance between the respiratory droplets is 5 (the first column) and 6 (the second column). The normalized diameter of the second respiratory droplet for the specified dimensionless distance is 0.4.

Fig. 10. Two-dimensional view of the two-respiratory droplet deformation at the penetrating and splashing stages. The dimensionless distance between the respiratory droplets is 2 (the first column), 3 (the second column), and 4 (the third column). The normalized diameter of the second respiratory droplet for the specified dimensionless distance is 0.6.

Fig. 11. Two-dimensional view of the two-respiratory droplet deformation at the penetrating and splashing stages. The dimensionless distance between the respiratory droplets is 5 (the first column) and 6 (the second column). The normalized diameter of the second respiratory droplet for the specified dimensionless distance is 0.6.

to that of the smaller respiratory droplet collision (Figs. 8 and 9 versus Figs. 10 and 11). Similar to the previous case, the pressure increases in the area of contact of two respiratory droplets. Due to the higher inertia of the larger secondary respiratory droplet, the high-pressure zone is more penetrated inside the first respiratory droplet after the collision takes place. One of the important results obtained from Figs. 8 and 9 (or Figs. 10 and 11) is that by decreasing the distance between two respiratory droplets, the time of penetration decreases, and the main respiratory droplet rapidly splashes.

The time needed for the secondary respiratory droplet to catch up with the main respiratory droplet is called the *catch-up time* shown by t_c . Based on the work of Zhao *et al.* (2019a), if the location of the two respiratory droplets is close to each other, the catch-up time and the breakup time would become shorter. The catch-up time is defined as:

$$t_c = 0.51 \sqrt{\frac{8}{3C_{D0}}} l^* \left(1 - \frac{1 - e^{-z}}{1 + e^{-z}}\right)^{-1/2} \quad (7)$$

$$z = 4.7 \times 10^{-3} l^* + 1.3 \frac{Y}{D_0}$$

This correlation was obtained by performing the curve-fitting process on the data presented by Zhao *et al.* (2019a). Y/D_0 and C_{D0} are the normalized distance of the secondary respiratory droplet in the y-direction and the drag coefficient of the main respiratory droplet, respectively. The catch-up times calculated for our case—using Eq. (7)—are listed in Table 2.

5.1.2 Stage 2- Splashing

Fig. 8 ($t^* = 0.5$ and 0.8) demonstrates some snapshots of the two-dimensional two- respiratory-droplet breakup process at the second step called splashing. The main respiratory droplet transfigures to unequal and parallel coronas, which stretch in a radial direction. The origin of the birth of these coronas is the high momentum of the incoming secondary respiratory droplet, which is transferred to the main respiratory droplet without kinking at the boundary of the contact zone. The penetration of respiratory droplets into each other during an equal binary respiratory droplet collision has also been investigated by Passandideh-Fard and Roohi (2006), Acevedo-Malavé and García-Sucre (2011), Acevedo-Malavé (2012), and Zhao *et al.* (2019b). One of the main features of splashing is the disintegration of the thin liquid into smaller respiratory droplets at the early stages due to the manifestation of a thin liquid layer.

Figs. 12 and 13 ($t^* = 0.5$ and 0.8) show the details of the splashing of the main respiratory

Table 2. The catch-up time and breakup time calculated for the case of interaction of two respiratory droplets.

	Catch-up time (t_c)	Breakup time (t_b)
$d^* = 0.4, l^* = 2$	0.250	0.730
$d^* = 0.4, l^* = 3$	0.271	0.748
$d^* = 0.4, l^* = 4$	0.293	0.769
$d^* = 0.4, l^* = 5$	0.305	0.795
$d^* = 0.4, l^* = 6$	0.381	0.861
$d^* = 0.6, l^* = 2$	0.169	0.510
$d^* = 0.6, l^* = 3$	0.174	0.531
$d^* = 0.6, l^* = 4$	0.181	0.552
$d^* = 0.6, l^* = 5$	0.188	0.574
$d^* = 0.6, l^* = 6$	0.193	0.591
$d^* = 0.8, l^* = 2$	0.128	0.400
$d^* = 0.8, l^* = 3$	0.131	0.430
$d^* = 0.8, l^* = 4$	0.136	0.451
$d^* = 0.8, l^* = 5$	0.142	0.473
$d^* = 0.8, l^* = 6$	0.148	0.485

Fig. 12. Two-dimensional view of the two-respiratory droplet deformation at the penetrating and splashing stages. The dimensionless distance between the respiratory droplets is 2 (the first column), 3 (the second column), and 4 (the third column). The normalized diameter of the second respiratory droplet for the specified dimensionless distance is 0.8.

Fig. 13. Two-dimensional view of the two-respiratory droplet deformation at the penetrating and splashing stages. The dimensionless distance between the respiratory droplets is 5 (the first column) and 6 (the second column). The normalized diameter of the second respiratory droplet for the specified dimensionless distance is 0.8.

droplet after the collision of a larger secondary respiratory droplet, which leads to the creation of greater coronas with respect to the first case during a shorter catch-up time. Additionally, it is concluded that the initial distance between the respiratory droplets at this stage has a smaller influence on the flow pattern. The dimensionless breakup times of the main respiratory droplet with a normalized distance of 2 correspondings to the non-dimensional secondary respiratory droplet diameters of 0.6 and 0.4 are 0.64 and 0.71, respectively. The breakup times increase to 0.712 and 0.731 for the case with a normalized distance of 3.

Fig. 14 illustrates the variation of the aerosol width with respect to dimensionless distance. The results indicate that the aerosol width increases with decreases in the dimensionless distance. The secondary respiratory droplet suddenly stops and transfers its momentum to the stationary main respiratory droplet, and then the airborne cloud becomes visible during the mixing process. A low concentration of airborne is observed in the higher dimensionless distance between the respiratory droplets. In other words, the value of the transferred momentum to the main respiratory droplets decreases with an increase in the distance. Although the intermolecular forces greatly affect the surface tension, the variation of the aerosol width curves is related to the magnitude of the morphological forces acting on each respiratory droplet in the contact zone (Guan *et al.*, 2018; Carolo *et al.*, 2019). Followings are three principal forces acting on the main respiratory droplet:

- 1- The drag force flattens the respiratory droplet.
- 2- The surface tension force exerts a resistive force against the flattening and restores the respiratory droplet back to its initial shape.
- 3- Inertia of the secondary respiratory droplet accelerates the splashing process.

The interplay between the influences of the surface tension force and the external aerodynamic forces (the drag force and the inertia) initiates the creation of an airborne cloud. It should be noted that the variation of the surface tension coefficient with temperature is considered in our study. However, the magnitude of the surface tension force varies with the curvature of the interface. Clearly, the value of the curvature is highly dependent on the morphological forces in the contact zone, the relative humidity, and the ambient temperature. By decreasing the radius of curvature, the surface tension force increases in accordance with *Tolman's hypothesis* (Bartell, 2001; Shneider and Pekker, 2019).

Fig. 14. The width of aerosol variation versus dimensionless distance at high-speed wind of 50 km h^{-1} for the case of two-respiratory droplet interaction.

5.2 CASE B: THE THREE-RESPIRATORY- DROPLET COLLISION

Considering the collision of two secondary respiratory droplets with the main respiratory droplet, the breakup characteristics and the morphology of the main respiratory droplet in connection with other smaller respiratory droplets will be analyzed in this section. To generate the numerical results, four different positions for the smaller respiratory droplets were selected along with the following geometrical parameters:

- Case a: The dimensionless diameter of both small respiratory droplets is 0.4.
- Case b: The dimensionless diameter of both small respiratory droplets is 0.6.
- Case c: The diameter of the closest respiratory droplet to the main respiratory droplet is 0.6, and the diameter of the other respiratory droplet is 0.4.
- Case d: The diameter of the closest respiratory droplet to the main respiratory droplet is 0.4, and the diameter of the other respiratory droplet is 0.6.

All three respiratory droplets are in tandem arrangement along with the direction of the incoming high-speed wind flow. Similar to the previous case, the breakup and deformation of the main respiratory droplet are governed by two steps.

5.2.1 Stage 1- Penetration

Figs. 15 and 16 ($t^* = 0.01-0.3$) present snapshots of the two-dimensional three-respiratory droplet collision at the penetrating stage. The major difference between the two respiratory droplets and the three respiratory droplet deformations is that in the three respiratory droplet case, the last respiratory droplet hits the bowl-like shape of the liquid, which is formed after penetration of the first respiratory droplet. Therefore, the next collision takes place between the third respiratory droplet and the bowl-like structure with extremely thin walls, which leads to the verge of the splash. It is seen that due to the larger diameter of the second respiratory droplet, the thickness of the bowl-like shape and its diameter is greater in “Case b”, and the pressure reduces at the tip of the bowl. Additionally, a high-pressure zone is seen near the lee side of the first respiratory droplet due to the effect of the collision of the two other respiratory droplets.

The three respiratory-drop collision catch-up times for “Cases a to d” are calculated based on the final collision using Eq. (7), and the results are presented in Table 3. The largest and shortest collision times correspond to “Case a” containing small respiratory droplets and “Case d” with large respiratory droplets, respectively. This trend stems from the higher inertia of the incoming respiratory droplets in “Case a”, which speeds up the collision process.

5.2.2 Stage 2- Splashing

As shown in Figs. 16 and 17 ($t^* = 0.5$ and 0.8), following the previous stage, the main respiratory droplet converts the bowl-shaped part of the liquid into unequal and parallel coronas. This stage of the three-respiratory-droplet breakup is similar to the final stage of the two-respiratory-droplet deformation process. As the material strips off the bowl liquid edge by the surrounding high-speed wind flow, the thickness of the coronas rapidly decreases. The smaller rate of feeding the film with transferred momentum causes the thin bowl-like liquid to splash at a shorter time. The dimensionless mixing times of the main respiratory droplet for Cases a, b, c, and d are 0.387, 0.301, 0.357, and 0.376, respectively. The presence of small neighboring respiratory droplets reduces the breakup time by approximately 5%. However, the presence of two small neighboring respiratory droplets results in a change of approximately 7% in the catch-up time.

6 THE EFFECTS OF WIND VELOCITY ON AEROSOL CLOUD

Our numerical study revealed how micro-respiratory droplets—during coughs and sneezes—can be dispersed in aerosol clouds, precisely the same as the real condition. Figs. 17 and 18 show the width of aerosol-cloud variation with the various wind velocities for two- and three-respiratory droplet splashing, respectively. First, the respiratory droplets expelled from the mouth are mostly affected by the inertia force and are moving along the direction of the high-speed wind velocity. These respiratory droplets interact with each other and convert to aerosol clouds under high-speed wind conditions. The results show that the aerosol width increases with an increase in the high-speed wind velocity. During the high-speed wind flow, some of the larger respiratory droplets

Fig. 15. Two-dimensional view of the three-respiratory-droplet breakup in high-speed wind flow at the penetrating and splashing stages. The first and second columns of each time correspond to “Cases a and b”, respectively.

Fig. 16. Two-dimensional view of the three-respiratory-droplet breakup in high-speed wind flow at the penetrating and splashing stages. The first and second columns of each time correspond to “Cases c and d”, respectively.

Table 3. The catch-up time calculated for the case of interaction of two respiratory droplets.

	Catch up time (t_c)	Breakup time (t_b)
Case a	0.123	0.387
Case b	0.107	0.301
Case c	0.114	0.357
Case d	0.120	0.376

Fig. 17. Variation of the wind velocity on the width of the aerosol corresponding to the two-respiratory droplet case.

Fig. 18. Variation of the wind velocity on the width of the aerosol corresponding to the three-respiratory droplet case.

fell on the floor, and some of them converted to smaller droplets during violent interaction. The smaller particles of respiratory droplets under high-speed wind conditions continue to fluctuate and take considerable time to reach the ground. The high-speed wind velocity increases the concentration of the airborne and may influence the infection's intensity and progression.

7 THE EFFECTS OF THE RELATIVE HUMIDITY AND AMBIENT TEMPERATURE ON AEROSOL CLOUD

Respiratory droplets can convert to clouds of airborne, viruses, and very small respiratory droplets on the high-speed wind flow by collision and breakup of the larger respiratory droplets. The width and thickness of the created aerosol vary in different situations. To determine the effect of the climate on the exhaled respiratory droplets, we considered the ambient temperature and the ambient humidity. We have previously studied the effects of RH and temperature on the survival of SARS-CoV-2 (Rezaei *et al.*, 2020). Rezaei *et al.* (2020) demonstrated that SARS-CoV-2 rapidly disappears in a condition with a temperature range of 50°C–80°C and a relative humidity range of 40%–50%. However, the current study focused on the outdoor transmission of SARS-CoV-2 at a windy condition, which differs from the indoor situation with zero-wind velocity. The mechanism of the effect of relative humidity on the virus survival is important and the climate situation should be considered to achieve precise results. Based on Moriyama *et al.* (2020) and Ahlawat *et al.* (2020) studies, relative humidity of 40–60% was found to be appropriate for limiting respiratory virus transmission in indoor places. The present study showed that a relative humidity level of 40–70% at high-speed wind velocity is not appropriate for the inactivation of viruses inside micro-droplets. This contradiction originated from parameters such as high-speed wind velocity, Water activity, surface inactivation, and salt toxicity in the virus's persistence in experimental studies. (Yang *et al.*, 2012). Various researches such as Dbouk and Drikakis (2020c), Vinoj *et al.* (2020) affirm our results. In this study, by adding of conservation of species for the specific humidity to the VOF solver, the effect of RH on the width of the aerosol. Figs. 19–22 show the variation of the aerosol width with the RH and temperature for all simulation cases during the collision. Our results indicate that exposing exhaled respiratory droplets to a higher ambient temperature and lower RH reduces the aerosol size. At higher ambient temperature and lower humidity (Dbouk and

Fig. 19. Variation of the ambient temperature on the width of the aerosol corresponding to the two-respiratory droplet case.

Fig. 20. Variation of the ambient temperature on the width of the aerosol corresponding to the three-respiratory droplet case.

Fig. 21. Variation of the ambient relative humidity (RH) on the width of the aerosol corresponding to the two-respiratory droplet case.

Drikakis, 2020c), the study concluded that protein is a crucial component of the virus structure. This protein is very unstable in the mentioned ambient situation, similar to the higher wind velocity.

8 THE ROLE OF FACE MASK WEARING IN THE CONTROL OF COVID-19

Nowadays, the crucial protective effect of face mask against SARS-CoV-2 has been highlighted by all scientific authorities (Feng *et al.*, 2020; Pei *et al.*, 2020). The spreading of viruses such as a

Fig. 22. Variation of the ambient relative humidity (RH) on the width of the aerosol corresponding to the three respiratory droplet case.

SARS-CoV-2 increase when the breakup time of the respiratory droplets decreases to 0.301. The number of respiratory droplet concentrations in the ambient air depends on the usage of the face mask during sneezing and coughing. It is important to note that these respiratory droplets collide with neighboring respiratory droplets under high-speed wind conditions and convert to very small airborne respiratory particles (approximately 500 nanometers). These particles (airborne SARS-CoV-2) significantly increase the risk of transmission of COVID 19. By wearing a face mask, the number of respiratory droplets—upon sneezing or coughing—decrease, that in turn, decreases the formation of very small airborne particles and infectivity of COVID-19. In the following, we have provided learning tips for public health impact and SARS-CoV-2 control in outdoor transmission:

- Wearing a face mask and keeping the social distance in outdoor environments are suggested.
- If a face mask is not used (for any reason), try to cover the two openings of the airway (i.e., the nose and mouth) in a windy condition.
- Apply a dehumidifier in air supply ducts in heating and ventilating systems.

9 CONCLUSIONS

Respiratory flow—expelled by a human during sneezing, coughing, or loudly talking—consists of a poly-dimension/distance collection of respiratory droplets/particles. In this article, we have presented a novel technique for the collision, deformation, and breakup of respiratory droplets under high-speed wind conditions. We considered the two- and three-respiratory droplets in these situations to calculate the breakup and catch-up time and study the morphology of the respiratory droplet in connection with other smaller respiratory droplets. We demonstrated the importance of face mask usage from a novel point of view. The mechanisms of the breakup, deformation, and collision of respiratory droplets in a high-speed wind stream of air were investigated. Three different positions of the respiratory droplets were selected, and the simulation of highly compressible two-phase flow was performed using the OpenFOAM C++ libraries. After validating the numerical results using the experimental data, several conclusions regarding the different features and regimes of respiratory droplet breakup and COVID-19 spreading were obtained as follows:

- 1) The use of the face mask will provide good prevention of respiratory droplet transmission during sneezing, coughing, or loudly talking in high-speed wind conditions.
- 2) The diameters and the distances between the expelled respiratory droplets (concentration of SARS-CoV-2) during sneezing and coughing depend on the usage of the face mask.

- 3) The spreading of the SARS-CoV-2 aerosol depends on the respiratory droplet breakup time. The spreading of SARS-CoV-2 increases with a decrease in respiratory droplet breakup time.
- 4) The deformation process for the one-respiratory droplet case is classified into three stages.
 - The appearance of the surface instability,
 - Flattening the respiratory droplet,
 - Entrainment from the liquid sheet.
- 5) The deformation process for two- and three-respiratory-droplet collisions is categorized into two steps:
 - penetration of the smaller respiratory droplets into the main respiratory droplet,
 - splashing of the main respiratory droplet.
- 6) The thickness of the deformed main respiratory droplet and the volume fraction of the liquid have been taken as two criteria to define the dimensionless breakup time. As a result, the normalized breakup time of the respiratory droplet at the high-speed wind has been computed to be approximately 0.301 and 0.4 for three- and two-respiratory droplet interactions, respectively.
- 7) The temporal variation of the center of mass velocity of the main respiratory droplet has been studied for two- and three-respiratory droplet cases. The velocity increases with time until a minimum point appears in the curve for each collision. The analysis of the results showed that this pattern of change *depends* on the morphological force acting on the respiratory droplets during the mixing process.
- 8) The advanced stages of the breakup of the resulting respiratory particle clouds have been observed, and a clear definition and quantification of the respiratory droplet breakup times have been offered.
- 9) As a result, with an increase in the wind velocity and the ambient relative humidity, the spreading of viruses increases. Also, with a decrease in the ambient temperature, mentioned spreading increases.

NOMENCLATURE

a	= acceleration (m s^{-2})
C_D	= drag coefficient
D_0	= initial respiratory droplet diameter (m)
F	= morphology force (N)
Re	= Reynolds number
t^*	= breakup time (s)
t_c	= catch up time (s)
u	= velocity (m s^{-1})
ρ_l	= density of liquid (kg m^{-3})
ρ_g	= density of gas (air) (kg m^{-3})

Subscripts

g	= gas
l	= liquid
c	= catch up

DATA AVAILABILITY

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

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REFERENCES

- Acevedo-Malavé, A. (2012). Hydrodynamics coalescence collision of three liquid drops in 3D with smoothed particle hydrodynamics. *AIP Adv.* 2, 042106. <https://doi.org/10.1063/1.4757966>
- Acevedo-Malavé, A., García-Sucre, M. (2011). Coalescence collision of liquid drops I: Off-center collisions of equal-size drops. *AIP Adv.* 1, 032117. <https://doi.org/10.1063/1.3624553>
- Ahlawat, A., Wiedensohler, A., Mishra, S.K. (2020). An overview on the role of relative humidity in airborne transmission of SARS-CoV-2 in indoor environments. *Aerosol Air Qual. Res.* 20(9), 1856–1861. <https://doi.org/10.4209/aaqr.2020.06.0302>
- Ameri, A., Rahnama, N., Bozorgmehr, R., Mokhtari, M., Farahbakhsh, M., Nabavi, M., Shoaee, S.D., Izadi, H., Yousefi Kashi, A.S., Dehbaneh, H.S., Taghizadeh-Hesary, F. (2020). Low-dose whole-lung irradiation for COVID-19 pneumonia: Short course results. *Int. J. Radiat. Oncol. Biol. Phys.* 108, 1134–1139. <https://doi.org/10.1016/j.ijrobp.2020.07.026>
- Ameri, A., Ameri, P., Rahnama, N., Mokhtari, M., Sedaghat, M., Hadavand, F., Bozorgmehr, R., Haghighi, M., Taghizadeh-Hesary, F. (2021). Low-dose whole-lung irradiation for COVID-19 pneumonia: Final results of a pilot study. *Int. J. Radiat. Oncol. Biol. Phys.* 109, 859–866. <https://doi.org/10.1016/j.ijrobp.2020.11.065>
- Asadi, S., Wexler, A.S., Cappa, C.D., Barreda, S., Bouvier, N.M., Ristenpart, W.D. (2019). Aerosol emission and superemission during human speech increase with voice loudness. *Sci. Rep.* 9, 2348. <https://doi.org/10.1038/s41598-019-38808-z>
- Bartell, L.S. (2001). Tolman's δ , surface curvature, compressibility effects, and the free energy of drops. *J. Phys. Chem. B* 105, 11615–11618. <https://doi.org/10.1021/jp011028f>
- Berberović, E., van Hinsberg, N.P., Jakirlić, S., Roisman, I.V., Tropea, C. (2009). Drop impact onto a liquid layer of finite thickness: Dynamics of the cavity evolution. *Phys. Rev. E* 79, 036306. <https://doi.org/10.1103/PhysRevE.79.036306>
- Bhardwaj, R., Agrawal, A. (2020). Tailoring surface wettability to reduce chances of infection of COVID-19 by a respiratory droplet and to improve the effectiveness of personal protection equipment. *Phys. Fluids* 32, 081702. <https://doi.org/10.1063/5.0020249>
- Bourouiba, L. (2020). Turbulent gas clouds and respiratory pathogen emissions: Potential implications for reducing transmission of COVID-19. *JAMA* 323, 1837–1838. <https://doi.org/10.1001/jama.2020.4756>
- Carelli, P. (2020). A physicist's approach to COVID-19 transmission via expiratory droplets. *Med. Hypotheses* 144, 109997. <https://doi.org/10.1016/j.mehy.2020.109997>
- Carrolo, G., Ribeiro, D., Barata, J.M., Silva, A.R. (2019). Aerodynamic Breakup of a Single Droplet due to a Crossflow Airstream, in: *AIAA Scitech 2019 Forum*, American Institute of Aeronautics and Astronautics. <https://doi.org/10.2514/6.2019-0628>
- Chaudhuri, S., Basu, S., Kabi, P., Unni, V. R., Saha, A. (2020). Modeling the role of respiratory droplets in Covid-19 type pandemics. *Phys. Fluids* 32, 063309. <https://doi.org/10.1063/5.0015984>
- Chen, L.D. (2020). Effects of ambient temperature and humidity on droplet lifetime – A perspective of exhalation sneeze droplets with COVID-19 virus transmission. *Int. J. Hyg. Environ. Health* 229, 113568. <https://doi.org/10.1016/j.ijheh.2020.113568>
- Chen, X., Zhou, X., Xia, X., Xie, X., Lu, P., Feng, Y. (2020). Modeling of the transport, hygroscopic growth, and deposition of multi-component droplets in a simplified airway with realistic thermal boundary conditions. *J. Aerosol Sci.* 151, 105626. <https://doi.org/10.1016/j.jaerosci.2020.105626>
- Dbouk, T., Drikakis, D. (2020a). On coughing and airborne droplet transmission to humans. *Phys. Fluids* 32, 053310. <https://doi.org/10.1063/5.0011960>
- Dbouk, T., Drikakis, D. (2020b). On respiratory droplets and face masks. *Phys. Fluids* 32, 063303. <https://doi.org/10.1063/5.0015044>
- Dbouk, T., Drikakis, D. (2020c). Weather impact on airborne coronavirus survival. *Phys. Fluids* 32, 093312. <https://doi.org/10.1063/5.0024272>
- Deshpande, S.S., Anumolu, L., Trujillo, M.F. (2012). Evaluating the performance of the two-phase flow solver interFoam. *Comput. Sci. Discovery* 5, 014016. <https://doi.org/10.1088/1749-4699/5/1/014016>

- Drossinos, Y., Stilianakis, N.I. (2020). What aerosol physics tells us about airborne pathogen transmission. *Aerosol Sci. Technol.* 54, 639–643. <https://doi.org/10.1080/02786826.2020.1751055>
- Feng, S., Shen, C., Xia, N., Song, W., Fan, M., Cowling, B.J. (2020). Rational use of face masks in the COVID-19 pandemic. *Lancet Respir. Med.* 8, 434–436. [https://doi.org/10.1016/S2213-2600\(20\)30134-X](https://doi.org/10.1016/S2213-2600(20)30134-X)
- Guan, B., Liu, Y., Wen, C.Y., Shen, H. (2018). Numerical study on liquid droplet internal flow under shock impact. *AIAA J.* 56, 3382–3387. <https://doi.org/10.2514/1.J057134>
- Guildenbecher, D.R., López-Rivera, C., Sojka, P.E. (2009). Secondary atomization. *Exp. Fluids* 46, 371. <https://doi.org/10.1007/s00348-008-0593-2>
- Hsiao, T.C., Chuang, H.C., Griffith, S.M., Chen, S.J., Young, L.H. (2020). COVID-19: An aerosol's point of view from expiration to transmission to viral-mechanism. *Aerosol Air Qual. Res.* 20, 905–910. <https://doi.org/10.4209/aaqr.2020.04.0154>
- Johns Hopkins University and Medicine (2020). COVID-19 mortality rate. <https://coronavirus.jhu.edu/map.html> (accessed 12 September 2020).
- Li, Y.Y., Wang, J.X., Chen, X. (2020). Can a toilet promote virus transmission? From a fluid dynamics perspective. *Phys. Fluids* 32, 065107. <https://doi.org/10.1063/5.0013318>
- Moriyama, M., Hugentobler, W.J., Iwasaki, A. (2020). Seasonality of respiratory viral infections. *Annu. Rev. Virol.* 7, 83–101. <https://doi.org/10.1146/annurev-virology-012420-022445>
- National Academies of Sciences, Engineering, and Medicine (2020). Rapid expert consultation on SARS-CoV-2 viral shedding and antibody response for the COVID-19 pandemic, April 8, 2020, pp. 1–7. <https://doi.org/10.17226/25774>
- Nazari, A., Jafari, M., Rezaei, N., Taghizadeh-Hesary, F., Taghizadeh-Hesary, F. (2021). Jet fans in the underground car parking areas and virus transmission. *Phys. Fluids* 33, 013603. <https://doi.org/10.1063/5.0033557>
- OpenFOAM Foundation Ltd. (2016a). OpenFOAM — the open source CFD toolbox — Programmers' guide. <https://www.openfoam.com/>
- OpenFOAM Foundation Ltd. (2016b). OpenFOAM — the open source CFD toolbox — User's guide. <https://www.openfoam.com/>
- Passandideh-Fard, M., Roohi, E. (2006). Coalescence collision of two droplets: Bubble entrapment and the effects of important parameters. 14th Annual (International) Mechanical Engineering Conference, Isfahan. <https://civilica.com/doc/27993/>
- Pei, C., Ou, Q., Kim, S.C., Chen, S.C., Pui, D.Y.H. (2020). Alternative Face masks made of common materials for general public: Fractional filtration efficiency and breathability perspective. *Aerosol Air Qual. Res.* 20, 2581–2591. <https://doi.org/10.4209/aaqr.2020.07.0423>
- Plog, J., Wu, J., Dias, Y.J., Mashayek, F., Cooper, L.F., Yarin, A.L. (2020). Reopening dentistry after COVID-19: Complete suppression of aerosolization in dental procedures by viscoelastic Medusa Gorgo. *Phys. Fluids* 32, 083111. <https://doi.org/10.1063/5.0021476>
- Rakhsha, A., Azghandi, S., Taghizadeh-Hesary, F. (2020). COVID-19 pandemic and patients with cancer: The protocol of a Clinical Oncology center in Tehran, Iran. *Rep. Pract. Oncol. Radiother.* 25, 765–767. <https://doi.org/10.1016/j.rpor.2020.07.001>
- Rezaei, N., Jafari, M., Nazari, A., Salehi, S., Talati, F., Torab, R., Nejad-Rahim, R. (2020). A novel methodology and new concept of SARS-CoV-2 elimination in heating and ventilating air conditioning systems using waste heat recovery. *AIP Adv.* 10, 085308. <https://doi.org/10.1063/5.0021575>
- Riediker, M., Morawska, L. (2020). Low exhaled breath droplet formation may explain why children are poor SARS-CoV-2 transmitters. *Aerosol Air Qual. Res.* 20, 1513–1515. <https://doi.org/10.4209/aaqr.2020.06.0304>
- Rodrigues, C., Barata, J., Silva, A. (2016). Modeling of droplet deformation and breakup. *J. Propuls. Power* 32, 698–706. <https://doi.org/10.2514/1.B35819>
- Schroter, R.C. (2020). Social distancing for covid-19: Is 2 metres far enough? *BMJ* 369, m2010. <https://doi.org/10.1136/bmj.m2010>
- Shneider, M.N., Pekker, M. (2019). Surface tension of small bubbles and droplets and the cavitation threshold. *arXiv preprint arXiv:1901.04329*. <https://arxiv.org/abs/1901.04329>
- Siavashpour, Z., Taghizadeh-Hesary, F., Rakhsha, A. (2020). Recommendations on management of locally advanced rectal cancer during the COVID-19 pandemic: An Iranian consensus. *J*

- Gastrointest. Canc. 51, 800–804. <https://doi.org/10.1007/s12029-020-00454-4>
- Simpkins, P.G., Bales, E.L. (1972). Water-drop response to sudden accelerations. *J. Fluid Mech.* 55, 629–639. <https://doi.org/10.1017/S0022112072002058>
- Smits, A.J., Dussauge, J.P. (2006). *Turbulent shear layers in supersonic flow*. Springer Science & Business Media. <https://www.springer.com/gp/book/9780387261409>
- Sun, C., Zhai, Z. (2020). The efficacy of social distance and ventilation effectiveness in preventing COVID-19 transmission. *Sustainable Cities Soc.* 62, 102390. <https://doi.org/10.1016/j.scs.2020.102390>
- Taghizadeh-Hesary, F., Akbari, H. (2020). The powerful immune system against powerful COVID-19: A hypothesis. *Med. Hypotheses* 140, 109762. <https://doi.org/10.1016/j.mehy.2020.109762>
- Tryggvason, G., Bunner, B., Esmaeeli, A., Juric, D., Al-Rawahi, N., Tauber, W., Han, J., Nas, S., Jan, Y.J. (2001). A front-tracking method for the computations of multiphase flow. *J. Comput. Phys.* 169, 708–759. <https://doi.org/10.1006/jcph.2001.6726>
- Vinoj, V., Gopinath, N., Landu, K., Behera, B., Mishra, B. (2020). The COVID-19 spread in India and its dependence on temperature and relative humidity. *Preprints* 2020, 2020070082. <https://www.preprints.org/manuscript/202007.0082/v1>
- Wang, D., Sun, B.C., Wang, J.X., Zhou, Y.Y., Chen, Z.W., Fang, Y., Yue, W.H., Liu, S.M., Liu, K.Y., Zeng, X.F., Chu, G.W., Chen, J.F. (2020). Can masks be reused after hot water decontamination during the COVID-19 pandemic? *Engineering* 6, 1115–1121. <https://doi.org/10.1016/j.eng.2020.05.016>
- Wilson, N.M., Norton, A., Young, F.P., Collins, D.W. (2020). Airborne transmission of severe acute respiratory syndrome coronavirus-2 to healthcare workers: A narrative review. *Anaesthesia* 75, 1086–1095. <https://doi.org/10.1111/anae.15093>
- Xie, X., Li, Y., Chwang, A.T.Y., Ho, P.L., Seto, W.H. (2007). How far droplets can move in indoor environments—revisiting the Wells evaporation–falling curve. *Indoor Air* 17, 211–225. <https://doi.org/10.1111/j.1600-0668.2007.00469.x>
- Xie, X., Li, Y., Sun, H., Liu, L. (2009). Exhaled droplets due to talking and coughing. *J. R. Soc. Interface* 6, S703–S714. <https://doi.org/10.1098/rsif.2009.0388.focus>
- Yan, J., Grantham, M., Pantelic, J., de Mesquita, P.J.B., Albert, B., Liu, F., Ehrman, S., Milton, D.K., Consortium, E. (2018). Infectious virus in exhaled breath of symptomatic seasonal influenza cases from a college community. *PNAS* 115, 1081–1086. <https://doi.org/10.1073/pnas.1716561115>
- Yang, W., Marr, L.C. (2012). Mechanisms by which ambient humidity may affect viruses in aerosols. *Appl. Environ. Microbiol.* 78, 6781–6788. <https://doi.org/10.1128/AEM.01658-12>
- Zhang, T. (2011). *Study on Surface Tension and Evaporation Rate of Human Saliva, Saline, and Water Droplets (MS)*. West Virginia University Libraries. <https://doi.org/10.33915/etd.2271>
- Zhao, H., Wu, Z., Li, W., Xu, J., Liu, H. (2019a). Interaction of two drops in the bag breakup regime by a continuous air jet. *Fuel* 236, 843–850. <https://doi.org/10.1016/j.fuel.2018.09.067>
- Zhao, W., Zhang, Y., Xu, B. (2019b). An improved pseudopotential multi-relaxation-time lattice Boltzmann model for binary droplet collision with large density ratio. *Fluid Dyn. Res.* 51, 025510. <https://doi.org/10.1088/1873-7005/aae443>
- Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., Song, J., Zhao, X., Huang, B., Shi, W., Lu, R., Niu, P., Zhan, F., Ma, X., Wang, D., Xu, W., Wu, G., Gao, G.F., Tan, W. (2020). A novel coronavirus from patients with pneumonia in China, 2019. *N. Engl. J. Med.* 382, 727–733. <https://doi.org/10.1056/NEJMoa2001017>