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

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Investigation on the evaporation and dispersion of human respiratory droplets with COVID-19 virus

Jing Yin, Leslie Kojo Norvihoho, Zhi-Fu Zhou, Bin Chen, Wei-Tao Wu

A State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi, 710049, PR China
B School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, PR China

ARTICLE INFO

Keywords:
SARS-CoV-2 transmission
Respiratory droplets
Evaporation
Droplet transport
Expiratory activities

ABSTRACT

On March 11, 2020, COVID-19 was declared as a pandemic by World Health Organization (WHO). Effective prevention is indispensable for defeating the ongoing COVID-19 pandemic. The evaporation and diffusion characteristics of the droplet in the air are the critical factors for the virus transmission by droplets. To better understand transmission routes of COVID-19 through respiratory droplets, a new evaporation and dispersion model for respiratory droplets is proposed to estimate droplet lifetime and the size of spreading zone in air. The importance of respiratory activities and environmental factors on the transmission of respiratory viruses are further discussed. The predictive results demonstrate initial particle size, ambient temperature and relative humidity all have significant effect on the survival time and infection distance of respiratory droplets. Decreasing droplet initial size always shortens the lifetime and the transmission distance of respiratory droplets. The 100 μm droplets expelled by talking or coughing can be carried more than 2 m away. Increasing ambient temperature and decreasing ambient humidity can effectively reduce the lifetime and propagation distance of respiratory droplets, thus reducing the risk of viral infection. These findings could contribute to developing effective prevention measures for controlling infectious disease transmission via droplets.

1. Introduction

Currently, the worldwide outbreak of the novel coronavirus virus disease 2019 (COVID-19) has provoked a dramatic threat and loss to human health, daily life and economy. The virus causing the disease is officially named severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) (Gorbalenya et al., 2020). According to the latest report from the World Health Organization (WHO), as of August 2021, there have been more than 210 million confirmed cases with 4.4 million deaths worldwide. To date, the most eye-popping change of SARS-CoV-2 is that the emergence of its variants and the improvement of its ability to spread between humans (Lessells, 2021). Due to the Delta mutant strain, since June 30, the number of newly infected people per day exceeded 20000 in Britain. All the signs indicate that fighting against COVID-19 may be a protracted war. Therefore, it is necessary to provide the systematic study for exploring the transmission mechanisms of the virus-related infectious diseases such as COVID-19, so as to develop effective measures to contain the infection. A great deal of evidence gathered from the confirmed cases of the COVID-19 (Holland et al., 2020; Somsen et al., 2020; van Doremalen et al., 2020; Vuorinen et al., 2020; Zhang et al., 2020) has proved that the primarily transmission routes of SARS-CoV-2 virus are through respiratory droplets and human-to-human contact, as well as aerosol transmission possibly.

For a long time, abundant investigations (Bahl et al., 2021; Duguid, 1946; Gralton et al., 2011; Jennson, 1942; Papinini and Rosenthal, 1997) have shown that infected people could expel droplets with different sizes into the air through various expiratory activities like sneezing, coughing, speaking and breathing, and the droplets carry massive pathogenic virus and bacteria. As shown in Fig. 1, there are two types of respiratory transmission through virus-laden droplets and droplet nuclei: droplet and airborne (Delikhoon et al., 2021; Holland et al., 2020). Dominated by the gravitational and inertial effects, larger droplets deposit relatively rapidly and are inhaled or contacted by susceptible people within a short distance, as a result, droplet transmission occurs. The other smaller droplets keep evaporating until the solid droplet nuclei are left. The evaporated droplet residues can remain suspended in air for long periods of time, causing airborne transmission. Generally, pathogens are not exclusively transmitted by droplets or airborne, but also by both routes simultaneously. Additionally, a clear distinction between two modes is of significance to prevention and control the spread of respiratory disease. The ‘critical size’ defining as...
the particle size is usually employed to distinguish droplet transmission and airborne transmission modes. Critical size is a function of many physical parameters, such as ambient temperature, ambient humidity, airflow velocity and so on. The previous work demonstrates that the critical size can be set at 5 µm (Asadi et al., 2020; Delikhoon et al., 2021; Liu et al., 2017a; Nicas et al., 2005). The ‘critical distance’ is defined as the farthest horizontal distance of infection caused by droplet transmission. The critical size and critical distance are closely related to the evaporation process of droplet particles. To mitigate the COVID-19 pandemic through such respiratory droplets, the so-called “6-foot rule” or “2-meter distance rule” is recommended by authorities all over the world (Guzman, 2021; Holland et al., 2020). Above policies of social distancing have been proved to be effective in combatting the COVID-19. However, 6-foot distance is decided based on the assumption of static ambient air, which neglects the effect of relative humidity (Drossinos and Stilianakis, 2020). Thus, the minimum distance between the infected and a host is still a subject of considerable debate. Reviewing the studies of horizontal distance travelled by respiratory droplets, the research by Bahl (Bahl et al., 2020) shows that distances reached by droplets carried with the SARS-CoV-2 virus is far greater than 2 m. Balachandar and Bourouiba (Balachandar et al., 2020; Bourouiba, 2020) stressed that droplets generated by sneezing can travel as far as 7-8 m due to the entrainment of the exhaled puff and ambient air turbulence. In the recent work (Liu et al., 2021a; Liu et al., 2021b), the

![Image of Nomenclature table]

**Fig. 1.** Two dominant transmission routes of SARS-CoV-2 (a) droplet transmission route with particles >5 µm (b) airborne transmission route by smaller airborne droplets and droplet nuclei.
turbulent evolution of an exhaled puff emitted by coughs/sneeze are explored using large eddy simulations, while the trajectory of each virus-laden droplet is individually tracked using the point-particle Euler–Lagrange approach. Taking droplet cloud dynamics into account, Liu’s present researches are of great value and provide a model to study the impact of turbulence in a detailed manner. The above high-quality simulation work also demonstrates that the theoretical framework of Balachandar (Balachandar et al., 2020) could accurately predict the behaviors of the ejected puff and the respiratory droplet nuclei under varying ejection conditions.

The existing research on the evaporation and sedimentation of a single droplet (Zuo et al., 2013) found that the size of the droplet with the virus not only plays a singularly important role in determining the movement and lifetime of the droplet in the air, but also the survival rate and infectious ability of the virus aerosol. Droplets were simplified as droplet nuclei in most of early numerical studies. As a result, droplet evaporation and size change on droplets movement were usually neglected (Chen and Zhao, 2009; Yan et al., 2019). However, the droplet evaporation is of vital importance in the eventual fate of a droplet (Nicas et al., 2005; Wells, 1934), especially for medium size droplets (e.g. 50 µm) (Wei and Li, 2015). A comprehensive review was conducted by Mao et al. (2020) for the physical process and transmission risk of respiratory droplets with different sizes at different times, which evidently proved that the disease transmission ability of large droplets was significantly greater than that of small droplets. Mittal et al. (2020) summarized the basic mechanisms of exhaled droplets formation and their subsequent evaporation processes. Stadnytskyi et al. (2020) used highly sensitive laser light scattering to observe the airborne lifetime of the speech droplets and assessed the possibility of small droplets in SARS-CoV-2 transmission in a closed environment. Feng et al. (2020) mimics the actual processes of SARS-CoV-2 laden droplets emitted by coughs using a validated computational fluid-particle dynamics (CFPD) model, to quantify the environmental wind and relative humidity (RH) effects on the droplet transmission between two virtual persons. Bourouiba (2020), Chong et al. (2021), Ng et al. (2021) suggested that the evaporation or deposition rate of SARS-CoV-2 laden droplets was not only affected by the particle size and the environmental conditions (temperature, humidity, and air flow), but also by the interaction between virus-laden droplets and ambient turbulence. Chen (2020) investigated the potential effects of the droplet size, ambient temperature and relative humidity on the evaporation lifetime of SARS-CoV-2 laden droplets in air through a simple evaporation model. From above literature review, much progress has been made to advance our understanding of the transmission of SARS-CoV-2 laden respiratory droplets. However, most of the reported evaporation models of human exhaled droplets are relatively simple, ignoring the influence of liquid recirculation and droplet internal temperature distribution inside droplet. In particular, the role of environmental factors on the spread of COVID-19 by respiratory droplets remains contentious and inconclusive (Bhagat et al., 2020; Bhardwaj and Agrawal, 2020; Casanova et al., 2010; Chen, 2020; Chong et al., 2021; Delikhooon et al., 2021; Eslami and Jalili, 2020; Feng et al., 2020; Moriyama et al., 2020; Ng et al., 2021; Prata et al., 2020).

In this study, a new droplet evaporation model considering the droplet internal temperature distribution and evaporation has been proposed to estimate the evaporation and motion of respiratory droplets in air. Moreover, a comprehensive investigation on the effects of environmental factors (e.g., temperature and relative humidity) and the initial parameters of droplets considering different modes of respiratory activities (e.g., sneezing, coughing, speaking and breathing) on the predictive results have been conducted.

2. Theoretical model of moving droplet evaporation

As shown in Fig. 2, there exists momentum, heat and mass transfer between evaporation droplet and its surrounding gaseous phase after a droplet is exhaled by respiratory activities. In particular, the viscous shear stress acting on the droplet surface is likely to cause internal circu-lation inside droplet if there exists a relatively large motion between droplet and the ambient gas. This momentum, heat and mass transfer, and internal circulation all affect the lifetime and transmission of respiratory droplet.

2.1. Mass transfer

The human respiratory droplets mainly comprise water (~90 to 99%) and other small part constituents like sodium chloride, glycoproteins, and, potentially, pathogens (Božić and Kanduc, 2021). Therefore, it is reasonable to treat respiratory droplet as pure water. In fact, the infectious droplets are assumed as pure water in most of previous numerical studies about exhaled droplets’ evaporation (Chen, 2020; Ji et al., 2018; Liu et al., 2019; Morawska, 2006; Parienta et al., 2011; Wei and Li, 2015). Few studies took NaCl solution to represent exhaled droplets (Haghnegahdar et al., 2019; Li et al., 2018; Liu et al., 2019; Morawska, 2006; Parienta et al., 2011; Wei and Li, 2015). It was found that droplet with NaCl or sputum constituent would lead to a relatively longer evaporation time. However, these effects are quite limited in contrast to the droplet size, ambient temperature and relatively humidity. Thus, in this work, we treat the respiratory droplet as pure water, and mainly focus on the effect of droplet initial parameters and environmental conditions on its evapo-ration and transmission. The mass transfer of water vapor at droplet interface is induced by mass diffusion due to the vapor concentration difference and Stefan flow due to convection. Based on the assumption that droplet is spherical and is insoluble to the air, then the total mass transfer rate \( \dot{m} \) on droplet surface can be expressed as (Miller et al., 1998):

\[
\dot{m} = \dot{m}_{Y,s} - 4\pi r^2 \Gamma \left. \frac{\partial Y_s}{\partial r} \right|_{r=r_{\infty}},
\]

where \( \Gamma \), \( Y_s \), \( r \) and \( \Gamma \) are the average density of the gas mixture near the drop surface, mass fraction of water vapor, the radial coordinate and the binary diffusion coefficient of liquid vapor in ambient gases, respectively. The subscript \( s \) refers to droplet surface.

The Sherwood number (\( Sh \)) and the Spalding mass transfer number (\( B_o \)) are defined from the following expression (Abramzon and Sirignano, 1989):

\[
Sh = \frac{2\pi r}{Y_{s,s} - Y_{s,\infty}} \left. \frac{\partial Y_s}{\partial r} \right|_{r=r_{\infty}},
\]

\[
B_o = 2\pi r Y_{s,\infty} \left. \frac{\partial Y_s}{\partial r} \right|_{r=r_{\infty}}.
\]
\[ B_M = \frac{Y_{v,s} - Y_{v,\infty}}{1 - Y_{v,s}} \]  

(3)

\[ Y_{v,s} \text{ and } Y_{v,\infty} \text{ are the mass fraction of vapor at the droplet’s surface and far from the droplet’s surface, which can be expressed as (Chen, 2020):} \]

\[ Y_{v,s} = \frac{X_{v,s} M_v + (1 - X_{v,s}) X_{v,\infty} M_v}{X_{v,s} M_v + (1 - X_{v,s}) [1 - (1 - X_{v,\infty}) M_{da} + X_{v,\infty} M_v]} \]  

(4)

\[ Y_{v,\infty} = \frac{d}{d + 1} \]  

(5)

where \( M_v \) and \( M_{da} \) correspond to the molar mass of water vapor and the dry air. \( X_{v,s} \) and \( X_{v,\infty} \) are the mole fraction of water vapor at the droplet’s surface and far from the droplet’s surface. \( d \) is indoor air humidity ratio, which is approximated as

\[ d = 0.622 \frac{P_g}{P_t} = 0.622 \frac{RH \times P_{v,\text{sat}}}{P_t - RH \times P_{v,\text{sat}}} \]  

(6)

where \( P_g, P_v, P_{v,\text{sat}} \) and \( RH \) are local atmospheric pressure, partial pressure of water vapor, the saturated vapor pressure of liquid and relative humidity for wet air, respectively.

\( X_{v,s} \) is calculated from the following equation:

\[ X_{v,s} = \frac{P_{v,s}}{P_g} \]  

(7)

where \( P_{v,s} \) is the saturated pressure of vapor at droplet’s surface. It can be calculated based on the Clausius-Clapeyron equation (Sazhin et al., 2010):

\[ P_{v,s} = P_v \exp \left[ \frac{L_v M_l}{R_g T_s} \left( \frac{1}{T_g} - \frac{1}{T_s} \right) \right] \]  

(8)

where \( R_g \) is the universal gas constant. \( T_g \) and \( T_s \) are the boiling temperature and the droplet surface temperature. Substituting Eqs. (2) and (3) into Eq. (1), then we can obtain the total evaporation rate of the droplet as followed,

\[ \dot{m} = 2 \pi r_d^2 \dot{r} S_h B_M. \]  

(9)

### 2.2. Heat transfer

Assuming that the convection heat supplied from the surrounding gas to the droplet is spent on droplet evaporation and raising its temperature, respectively, the energy equation at droplet surface can be presented in the form:

\[ 4 \pi r_d^2 h(T_s - T_g) = \dot{q}_i + \dot{m} L_v, \]  

(10)

where \( T_g \) is the ambient gas temperature; \( \dot{q}_i \) and \( L_v \) are the conductive heat toward the liquid interior to raise its own temperature and the latent heat of vaporization, respectively; \( h \) is the convection heat transfer coefficient which can be obtained through the Nusselt number \( h = \frac{Nu}{\pi r_d} \).

If we neglect the temperature gradient inside the droplet, then \( \dot{q}_i \) can be expressed as:

\[ \dot{q}_i = mc_p \frac{dT}{dt} \]  

(11)

where \( m \) and \( c_p \) are the droplet total mass and specific heat, respectively.

Substituting Eqs. (11) into (10), then we can obtain the overall temperature of the droplet that only varies with time.

\[ \frac{dT}{dt} = \frac{3L_v \dot{r} \dot{c}_p}{c_p \dot{r}_s} + \frac{3h(T_s - T_g)}{\rho_l c_p \dot{r}_s} \]  

(12)

where \( \dot{r}_s \) is droplet radius variation rate that can be derived from Eq. (9).

Eq. (12) is usually suitable for the conditions with low Reynolds number because of its uniform temperature distribution inside droplet. However, if there exists a relatively large motion between the droplet and its surrounding gas, the viscous shearing stress acting on the droplet surface leads to internal circulation inside droplet which makes the surface and central regions heated or cooled more quickly than the vortex center (stagnant point). As a result, the uniform temperature assumption might not be applied, especially during the transient heating stage.

A new energy balance equation was proposed in our previous work (Zhou et al., 2017) to consider the non-uniform temperature distribution due to the internal flow within droplet, that introduces an average temperature \( \overline{T} = \frac{3}{\pi} \int_0^r r^2 T(r) dr \), to replace the uniform temperature of Eq. (12).

\[ \frac{dT}{dt} = \frac{3 \dot{c}_p}{\dot{r}_s} \left( T_s - T_g \frac{L_v}{c_p} \right) + \frac{3h}{\rho_l c_p \dot{r}_s} \left( T_s - T_g \right). \]  

(13)

Further, based on the presence of internal flow described by Hill’s spherical vortex (Abramzon and Sirignano, 1989; Prakash and Sirignano, 1978; Tong and Sirignano, 1986) and the assumption of cubic polynomial temperature distribution within the moving droplet, \( T(r) = a + br + cr^2 + dr^3 \), the relationship between the surface and average temperature can be derived as:

\[ T_s = \overline{T} + 0.043 \frac{Nu T_s}{1 + 0.043 \frac{Nu}{T_s}} + 0.086 \frac{\rho_l \dot{c}_p \dot{r}_s}{(1 + 0.0435 Nu)} \]  

(14)

where \( \lambda_d \) is calculated as \( \lambda_d = \lambda / \lambda_l \).

The above treatment to consider the energy balance and non-uniform temperature distribution within droplet is called as 3\(^{rd}\)-order polynomial temperature profile model of droplet evaporation.

The correlations of \( Sh \) and \( Nu \) numbers that determine heat and mass transfer on droplet surface are inferred from the N-G-R-M correlations (Zhifu et al., 2013), combining the Narasimhan and Gauvin (N-G) (Narasimhan and Gauvin, 1967) and the Ranz and Marshall (R-M) (Ranz and Marshall, 1952) models:

\[ Nu = (1 + B_T)^{-2/3} \left( 2 + 0.6 R_e^{1/2} P_r^{1/3} \right). \]  

(15)

\[ Sh = (1 + B_M)^{-2/3} \left( 2 + 0.6 R_e^{1/2} S_c^{1/3} \right). \]  

(16)

where \( R_e, P_r, \) and \( S_c \) represent the Reynolds number, Prandtl number, and Schmidt number, respectively. \( B_T \) is the Spalding heat transfer number, which can be estimated as

\[ B_T = \frac{\tau_{v,g} (T_s - T_g)}{L + Q_j / \dot{m}} \]  

(17)

where \( \tau_{v,g} \) and \( L \) are the specific heat capacity of vapor and the latent heat of vaporization, respectively; \( Q_j \) is the heat spent on the change in droplet temperature.

### 2.3. Momentum exchange

The diameter of the droplets is critical to determine the motion and fates of droplets. The respiratory droplets smaller than 100 \( \mu \)m can float in the air with relatively long time and have the chance to be inhaled, while those larger than 100 \( \mu \)m would quickly settle (Mao et al., 2020). For the droplets with diameter less than 100 \( \mu \)m, the gravity force is usually neglected (Wells, 1934). Thus, droplet velocity is mainly dependent on the drag force acting by the ambient gas due to the relative motion. Then, the momentum equation can be presented as:
Fig. 3. Comparison between the experimental data and model predictive results of n-Decane droplet evaporation: (a) internal temperature distribution and (b) droplet diameter variation. (The experimental condition: $T_g = 1000$ K, $Re_0 = 17$, $To = 315$ K, $Do = 2$ mm from Ref. (Wong and Lin, 1992). (a) Droplet internal temperature distribution (b) droplet diameter variation.

Fig. 4. Variation of the droplet properties with different initial sizes as a function of time ($T_g = 20$ °C, RH = 40%, $Ve = 0.2$ m/s, $Te = 37$ °C, $Vo = 11.7$ m/s, $Do = 20$, 40 and 60 μm) (a) Droplet diameter (b) Droplet velocity (c) Average temperature of respiratory droplets. (a) Droplet diameter. (b) Droplet velocity. (c) Average temperature of respiratory droplets.
The lifetime and the maximum transmission distance of respiratory droplets (a) with varying sizes (\(T_s = 20 \, ^\circ C, \, RH = 40\%\), \(V_s = 0.2 \, m/s\), \(T_o = 37 \, ^\circ C\), \(D_o = 1, 5, 10, 20, 40, 60, 80\) and \(100 \, \mu m\), \(V_o = 10 \, m/s\)), and (b) with different initial velocities (\(T_s = 20 \, ^\circ C, \, RH = 40\%\), \(V_s = 0.2 \, m/s\), \(T_o = 37 \, ^\circ C\), \(D_o = 100 \, \mu m\), \(V_o = 1, 5, 10, 20, 30, 40\) and \(50 \, m/s\)). (a) droplets with varying sizes. (b) droplets with different initial velocities.

\[
dV_s = \frac{3}{8} \rho_l C_D (V_l - V_s)^2, \tag{18}
\]

where \(V_l\) and \(V_s\) are droplet and ambient gas velocities; \(\rho_l\) is the droplet density. \(C_D\) is the drag coefficient of discrete spherical droplets in the continuous phase, which is estimated by the empirical correlation proposed by (Victor et al., 1998):

\[
C_D = \frac{24}{Re_d} \left(1 + 0.197Re_d^{0.62} + 2.6 \times 10^{-3}Re_d^{1.38}\right), \tag{19}
\]

2.4. Numerical solution

The above mass, energy and momentum governing equations can be solved by using the fully implicit iterative methods. The main steps of numerical algorithm are given below:

1. The internal temperature distribution, diameter and velocity of the droplet from the initial conditions or the previous time step are obtained.
2. Calculate the molar fraction of water vapor near the drop surface (\(X_{v,s}\)) while ignoring the effect of humidity, then the value of \(Y_{v,s}\) and \(X_{v,s}\) are obtained based on Eqs. (4)-(8).
3. Calculate the physical properties of the liquid, such as \(\rho_l\), \(\lambda_l\), \(c_{pl}\).
4. Based on the “1/3” rule, calculate the average properties of the vapor–air mixture, such as \(\overline{\rho}_g\), \(\overline{\lambda}_g\), \(\overline{c}_g\), \(\overline{\rho}_g\).
5. Calculate the values of \(B_{TB}\), \(B_{T}\) and the dimensionless numbers such as \(Re_d\), \(Pr_g\), \(Sc_g\). Thus, the values of Nusselt and Sherwood numbers are estimated.
6. Solve the momentum exchange governing equation to obtain a new droplet’s velocity using Eq. (18).
7. A new droplet radius is obtained by solving the evaporation rate \(m\) on droplet surface using Eq. (9).
8. Solve the energy equation to obtain the internal temperature distribution of the droplet based on Eqs. (13)-(14).
9. Use the new droplet radius and surface temperature, repeat steps (1)-(10) until desired convergences are achieved simultaneously. The convergence criterions are taken as \(|r^{j+1} - r^j| > 10^{-6}\) and \(|T^{j+1} - T^j| > 10^{-6}\).

The superscript \(j\) and \(j+1\) refer to the values at the beginning and the end of the time step. If the convergence criterions are satisfied, then go to the next step.

10. Recalculate the droplet’s radius at the end of the time step \(\Delta t\).
11. Return to step (1) and move to the next time step.

2.5. Model validation

The model is validated by the experimental data of n-decane droplet evaporation by Wong and Lin (Wong and Lin, 1992). As can be seen in Fig. 3, the model predictions show reasonable agreement with the experimental data in the internal droplet temperature distribution and evaporation rate in terms of droplet diameter variation rate. The heat transportation from the droplet surface to the center is well reflected in this model that droplet surface and central temperatures increase more quickly than the vortex center (at \(r = 0.707r_o\)) due to the internal vortex circulation. More details can be found in our previous study (Zhou et al., 2017).

3. Results and discussions

3.1. Effects of respiratory activities

The spread of respiratory disease is associated with the characteristics of human droplets resulting from breathing, speaking, coughing and sneezing. Pathogens and virus attach to the droplets and transmit to the mouth and nasal of susceptible population with certain distance and short time. Thus, it is essential to know how droplet initial parameters and environmental factors affect droplet transmission distance and lifetime. In this section, the effects of respiratory activities on the evaporation and diffusion characteristics of human respiratory droplets, as predicted by the above droplet evaporation model, were investigated in detail. The initial temperature \(T_o\) of the exhalation droplet can be approximated as body temperature, that is 37 °C. The initial diameter of droplets ejected from a person usually ranges from 0.1 to 100 μm regardless of human status, gender and age (Gralton et al., 2011; Zhang et al., 2015). Droplets larger than 100 μm usually fall rapidly on the ground before evaporation (Li et al., 2018; Wells, 1934), thus they are not considered in this study. The droplet momentum treatment is assumed to be 1-Dimensional due to the large difference in ambient air velocity and initial droplet velocity. In addition, the ambient air flow is in the same direction as the exhaled droplet initial trajectory in the following analysis.

Fig. 4(a) depicts the diameter variation of respiratory droplets with three different initial diameters (20, 40 and 60 μm) versus time. It is assumed that most transmission events occur indoors. The indoor
ambient temperature $T_o$, relative humidity (RH) and air velocity $V_g$ in winter are set as $20 \degree C$, 40% and 0.2 m/s, respectively. The initial horizontal velocities $V_o$ of all droplets are set as 11.7 m/s to simulate exhalant droplet resulting from human coughing (Chao et al., 2009). As can be seen from this figure, all droplet diameters first presents nearly linear reduction with time due to the evaporation; Then the diameters decrease more quickly at the end of evaporation stage, which is mainly attributed to the increasing specific surface area due to the surface regression by droplet continuous evaporation. Droplet initial diameter has great impact on its lifetime. Large diameter droplet needs more time to evaporate completely. Specifically, it takes about 4.66 s for a 60 μm droplet to evaporate completely, while 2.07 s and 0.52 s for 40 μm and 20 μm droplets.

The effect of the initial diameter on droplet velocity variation versus time is illustrated in Fig. 4(b). As can be seen, the droplet motion can be divided into the deceleration process and constant velocity process. For droplets exhaled from the patient’s mouth, their initial velocity is much higher than the ambient air velocity. Due to the drag force, the droplet decelerates and reaches its terminal velocity in a very short time. Then the droplet and the airflow remain relatively static, and continue to move forward until complete evaporation. Smaller droplet velocity decreases more quickly compared with larger droplet, which means smaller droplet has shorter transmission distance and narrow spreading zone.

To evaluate the effect of evaporation on droplet temperature, Fig. 4(c) displays the average temperatures of respiratory droplets with different initial sizes versus time. During the whole vaporization period, all droplets temperatures with different sizes firstly experience a rapid decrease process and then follow by a slow decreasing rate before reaching their minimum temperatures. The first decrease in droplet temperature is attributed to the convective heat from the droplet to the surrounding gas and latent heat spent on droplet evaporation. As the droplet temperature is below ambient temperature, the input heat from the surrounding gas provides the energy for droplet vaporization. The minimum temperature of droplet appears once the input heat is balanced by the latent heat of vaporization. The initial size of respiratory droplets has a significant impact on droplet temperature variation in the decreasing stage. The smaller the droplet diameter is, the faster the temperature drops. However, all droplets have the same minimum temperature, which does not rely on droplet initial size.

Social distance policies have been proved to contribute to curtailing the SARS-CoV-2 virus spread. To quantify the minimum distance between the infected and a host with various droplet sizes, the evaporation time (lifetime) and the maximum transmission distance of respiratory droplets with varying sizes is summarized in Fig. 5(a). Eight sets of results are presented, representing eight different initial droplet diameters, $D_o = 1, 5, 10, 20, 40, 60, 80, \text{ and } 100 \mu m$, respectively. Given that viruses rely on the medium to remain alive, the droplet evaporation time is crucial to the survival time of the viruses and personal exposure risk. As can be seen, the lifetime of the droplets is significantly prolonged with the increase in the initial size of droplets. The evaporation time of droplets with diameter smaller than 10 μm is less than 0.2 s, while is about 12.9 s for a 100 μm droplet. Similar with droplet lifetime, the droplet’s travel distances along the horizontal direction increase significantly with the initial droplet diameter. It is observed that the expelled droplet with an initial diameter of 100 μm can transport more than 2 m away at an initial velocity of 10 m/s. This indicates that the 6-ft social distancing policy might not be sufficient to avoid the SARS-CoV-2 transmission through respiratory droplets. Considering the obvious intensity difference among different respiratory activities (Zhang et al., 2015), the velocity of the droplets produced by normal breathing is between 0.1 and 1 m/s; the talk-ejected droplet velocity is ranges from 2 to 10 m/s; whereas the velocity of cough-ejected droplet is 10-20 m/s, and the sneezing droplet can be ejected at speeds of up to 50 m/s. Fig. 5(b) shows the effect of droplet initial velocity on the lifetime and maximum transmission distance of respiratory droplets at the condition of $T_g = 20 \degree C, RH = 40\%$, $V_g = 0.2 \text{ m/s}$, $T_o = 37 \degree C, D_o = 100 \mu m$. Compared with the droplet initial diameter, initial velocity has far less influence on droplet lifetime and transmission distance. They present slight decrease and increase with the increasing of droplet velocity, respectively. The decrease of droplet lifetime at high initial velocity is attributed to the larger evaporation rate due to the greater convective heat transfer between droplet and ambient gas. However, it should be noticed that the predictive transmission distance does not consider the effect of exhaled flow induced by different respiratory activities. In reality, during coughing or sneezing, the virus-laden droplets are exhaled accompanying co-flows of exhaled gas. This can reduce the relative velocity difference between droplet and gas, which might make the effect of initial droplet velocity on distance travelled much stronger. It has already been observed by Liu et al. (2021a; b) that ejected puff resulting from a cough or sneezing can propagate particles over large distances through self-propelling vortex rings.

### 3.2. Effects of environmental factors

The temperature and relative humidity of environment play an important role in determining the lifetime and transmission distance of respiratory droplets, since they affect the mass and heat transfer of
vaporizing droplet. Fig. 6(a) shows the temporal evolution of the diameter of respiratory droplets under various environmental temperatures ($T_g = 10, 20$ and $30^\circ C$) and relative humidities ($RH = 20, 40$ and $60\%$). As can be seen, higher environmental temperature and lower humidity all lead to more rapid decrease in droplet diameter, indicating higher evaporation rate. Higher environmental temperature means larger mass diffusion coefficient of water molecule in air and more heat for droplet vaporization. In addition, lower humidity means larger driving force of mass transfer between droplet surface and ambient air. Another observation is the humidity effect on droplet evaporation at higher environmental temperature becomes less obvious compared with lower environmental temperature. This is probably because higher temperature air has larger capacity to hold water vapor, mitigating the change of driving force of mass transfer induced by environmental humidity.

Fig. 6(b) presents the temporal variation of the droplet’s average temperature at different $T_g$ ($T_g = 10, 20$ and $30^\circ C$) and RH ($RH = 20, 40$ and $60\%$). In general, all droplet temperatures initially experience a rapid decrease, and then decline gradually to a stable minimum temperature. Lower ambient temperature and relative humidity all lead to a larger decreasing rate and correspondingly, a lower stable temperature. However, $T_g$ and RH present different performance in affecting droplet temperature variation. Droplets minimum temperature depends on $T_g$, to a far larger extent, than on RH. Higher $T_g$ produces higher minimum temperature. Nevertheless, all droplet minimum temperatures are below the ambient temperatures in which they are located. When the minimum temperature appears, droplet enters a steady evaporation stage with no temperature change. The latent heat of vaporization is entirely provided by convective heat from the ambient gas.

The evaporation time (a) and transmission distance (b) of respiratory droplets with initial diameter of $10\, \mu m$ at different ambient temperatures and relative humidity ($T_g = 10, 20$ and $30^\circ C$, $RH = 0, 20, 40, 60$ and $80\%$, $V_g = 0.2\, m/s$, $T_o = 37^\circ C$, $D_o = 10\, \mu m$, $V_o = 11.7\, m/s$). (a) Droplet lifetime. (b) Max transmission distance.
droplet center as schematically shown in Fig. 2, as a result, droplet center and surface temperature changes more rapidly, while the stagnant point (vortex center around r/rₜ = 0.7) benefit less from this circulation with highest temperature. The internal temperature tends to become uniform with time. The principal reason for the small temperature gradient is the slow droplet evaporation and the enhancement of internal circulation on heat transfer.

Fig. 8. (a) depicts the lifetime of respiratory droplets with initial condition of Tₘ = 37 °C, Dₘ = 10 μm, Vₘ = 11.7 m/s at different ambient temperatures (Tₚ = 10, 20 and 30 °C) and relative humidities (RH = 0, 20, 40, 60 and 80%). The decrease of ambient temperature or the increase of relative humidity extends the lifetime of droplets. Droplet lifetime shows nearly linear variation with RH. However, the droplet lifetime growth rate with RH is more sensitive at low environmental temperature. In contrast to RH, the increase of Tₚ is superior to the decline of RH in enhancing the evaporation rate and reducing the possibility of infection via respiratory droplets, which is consistent with our prediction in Fig. 6(a). This dependence of droplet lifetime on Tₚ and RH offers good evidence that lower environmental temperature and higher humidity possesses greater risk of viral infection through respiratory droplets.

Corresponding to Fig. 8(a), the effect of RH and Tₚ on the droplet transmission distance is shown in Fig. 8(b). The transmission distance increases with RH, while decreases with Tₚ. This can be explained by the fact of the influence of RH and Tₚ on droplet lifetime. That is higher RH increases droplet lifetime, thus prolonging droplet spread distance; while higher Tₚ decreases droplet lifetime, shortening droplet spread distance.

4. Conclusions

This work conducted a numerical study to assess the effects of droplet size, droplet exhaled velocity, ambient temperature and relative humidity on virus-laden droplet dispersion based on the new droplet evaporation model, from the perspective of droplet transmission route. The primary conclusions can be summarized as follows:

There are obvious differences in the initial size and velocity of expelled droplets during normal breathing, talking, coughing and sneezing, which have an impact on the lifetime and spread range of infectious droplets. Droplet size mainly determines its evaporation and dispersion after being expelled. The larger droplet needs more time to evaporate completely in air under the same environmental condition, resulting in the longer propagation distance. Thus, the respiratory infection capacity of large droplets is much greater than that of small droplets. In contrast to droplet size, droplet initial velocity has much less influence on droplet evaporation and transmission. Higher velocity can increase slightly transmission distance.

Higher RH suppresses the droplet evaporation, whereas higher environmental temperature promotes the droplet evaporation. As a result, higher RH increases droplet lifetime and transmission distance, while higher environmental temperature shortens droplet lifetime and transmission distance. This demonstrates that the environment with lower temperature and higher RH possesses greater risk of viral infection through respiratory droplets.

Finally, it should be pointed out that the transmission by airborne particles or considering the ejected turbulent puff is far more complicated compared with droplet transmission (droplet diameter > 5 μm). Airborne particles may stay suspended in the air for much longer period of time or even have the ability to travel by air currents. And the accompanying co-flows of exhaled gas caused by different respiratory activities might change the transmission distance greatly. However, this paper only focused on large size droplet evaporation and dispersion and the influences of environmental and initial parameters on them. Therefore, the main conclusions obtained in this study only applies to virus propagation dominated by relatively large droplet transmission. More work is still urgently needed to better understand the transmission mechanism of COVID-19 in complex environment and contain the infection.

CRediT authorship contribution statement

Jing Yin: Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – original draft, Writing – review & editing. Leslie Kojo Norvihuho: Formal analysis, Writing – original draft. Zhi-Fu Zhou: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. Bin Chen: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. Wei-Tao Wu: Data curation, Investigation, Validation.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgement

We would like to acknowledge the support from Natural National Science Foundation of China (52176163), from Ministry of Science and Technology of China with the Key Program for International Science and Technology Cooperation Project (2017YFE0134200) and from the Ministry of Science and Technology of Shaanxi Province, China (2020KJXX-040). Thanks are also given to the Aerospace science fund (2019ZB070002).

Appendix

Tables 1 and 2.

### Table 1

The thermodynamic and transport properties of human respiratory droplets.

| Properties                  | Correlations where T = in °C |
|-----------------------------|-----------------------------|
| Molecular weight (g/mol)    | M = 18.01                   |
| Specific heat capacity of liquid (J/(kg.K)) | qᵥ = 4217.5 × 10⁻³ × T⁻² + 6.169 × 10⁻¹ × T³ |
| Specific heat capacity of vapor (J/(kg.K)) | qᵥ = 1.88454 × 10⁻³ × T + 5.12529 × 10⁻² × T² |
| Density of liquid (kg/m³)   | ρₗ = 1000 × 1.4662 × 10⁻³ × T + 0.00511 × T² |
| Density of vapor (kg/m³)    | ρᵥ = 0.00726 × 9.37543 × 10⁻⁵ × T + 2.9319 × 10⁻⁴ × T² |
| Liquid thermal conductivity (W/(m.K)) | λₗ = 0.5567024 × 2.3727 × 10⁻³ × T⁻¹ × 0.1369 × 10⁻⁴ × T² |
| Vapor thermal conductivity (W/(m.K)) | λᵥ = 0.01676115 × 0.6389 × 10⁻⁴ × T + 0.19003 × 10⁻⁶ × T² |
| Vapor viscosity (Pa·s)      | µᵥ = 0.894303 × 10⁻³ × 0.2905 × 10⁻⁷ × T + 0.502052 × 10⁻¹ × 10⁻² × T² |
| Latent heat of vaporization (J/kg) | L = 1000 × (2500.81327 × 2.35804 × T - 0.301628 × 10⁻³ × T²) |

### Table 2

The properties of ambient gas.

| T (°C) | Pᵥₑₑₑₑ (Pa) | Mᵥₑₑₑₑ (g/mol) |
|--------|-------------|----------------|
| 10     | 2339.3      | 28.97          |
| 20     | 4242        | 28.97          |
| 30     | 6128.1      | 28.97          |
References

Abrahonzon, B., Sirignano, W.A., 1989. Droplet vaporization model for spray combustion calculations. Int. J. Heat Mass Transf. 32, 1605-1618.

Asadi, S., Bouvier, N., Wesler, A., Rintenpart, W., 2020. The coronavirus pandemic and aerosols: Does COVID-19 transmit via exhalatory particles? Aerosol. Sci. Technol. 54, 635-638.

Bahl, P., de Silva, C., Bhattacharjee, S., Stone, H., Doolan, C., Chughtai, A.A., MacIntyre, C.R., 2020. Airborne and droplet transmission for healthcare workers treating coronavirus disease 2019? J. Infect. Dis. jia189. https://doi.org/10.1093/infdis/jia189.

Balarachandar, S., Zaleski, S., Soldati, A., Ahmadi, G., Bourouiba, L., 2020. Host-to-host airborne transmission as a multiphase flow problem for science-based social distance guidelines. Int. J. High Speed Flow 15, 103439.

Bhat, R., Wykes, M., Dalziel, S., Linden, P., 2020. Effects of ventilation on the indoor spread of COVID-19. J. Fluid Mech. 903, F1.

Bhardwaj, R., Agrawal, A., 2020. Likelihood of survival of coronavirus in a respiratory cough or sneeze to explain enhanced airborne transmission under dry weather. Sci. Rep. 11, 9826.

Bourdoua, R., Agravat, A., 2020. Likelihood of survival of coronavirus in a respiratory droplet deposited on a solid surface. Phys. Fluids 32, 061704.

Bozic, A., Kanduc, M., 2021. Relative humidity in droplet and airborne transmission of disease. J. Biol. Phys. 47, 1-29.

Bourouiba, L., 2020. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. JAMA 323, 1837-1838.

Casanova, L., Jeon, S., Rutoski, D., Weber, D., Sobsey, M., 2010. Effects of air temperature and relative humidity on coronavirus survival on surfaces. Appl. Environ. Microbiol. 76, 2712-2717.

Chao, C.Y.H., Wan, M.P., Morawski, L., Johnson, G.R., Ristovski, Z.D., Hargreaves, M., Mengesken, K., Corbett, S., Li, Y., Xie, K., Katsoshevski, D., 2009. Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. J. Aerosol. Sci. 40, 123-138.

Chen, C., Zhao, B., 2009. Some questions on dispersion of human exhaled droplets in ventilator room: answers from numerical investigation. Indoor Air 20, 90–111.

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, 115365.

Chong, K.L., Ng, C.S., Hori, N., Yang, R., Verzicco, R., Loch, D., 2020. Extended lifetime of respiratory droplets in a turbulent vapor puff and its implications on airborne disease transmission. Phys. Rev. Lett. 126, 034502.

Delikkoohan, M., Guzman, M., Nabiizadeh, R., Norouzian Baghani, A., 2021. Modes of transmission of severe acute respiratory Syndrome-Coronavirus-2 (SARS-CoV-2) and factors influencing on the airborne transmission: a review. Int. J. Environ. Res. Public Health 18, 393.

Drossinos, Y., Stillianakis, N., 2020. What aerosol physics tells us about airborne pathogen transmission. Aerosol. Sci. Technol. 54, 639-643.

Duguid, J.P., 1946. The size and the duration of air-carriage of respiratory droplets and droplet nuclei. J. Hyg. (Lond.) 44, 471-479.

Esmai, H., Jalili, M., 2020. The Role of Environmental Factors to Transmission of SARS-CoV-2 and factors influencing on the airborne transmission: a review. Int. J. Environ. Res. Public Health 18, 393.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.

Feng, Y., Marchal, T., Sperry, T., Yi, H., 2020. Influence of wind and relative humidity on pathogen transmission. Aerosol Sci. Technol. 54, 639-643.