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Influence of ambient conditions on evaporation and transport of respiratory droplets in indoor environment

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ABSTRACT

Respiratory droplets are playing a significant role in the transmission of any flu type disease as well as SARS-Cov-2 virus. The presence of pathogens affects the evaporation of the liquid droplets along with ambient temperature and relative humidity (rh). Complete evaporation of droplets leads to the formation of aerosol or droplet nuclei which remain suspended in the air for a longer period of time and get spread over larger distances increasing the risk of disease transmission. In present work, a droplet evaporation model has been formulated considering the droplet as a salt solution and the formation of crystals has been taken into account which will be analogous to the aerosol formation. After the establishment of the evaporation model, the trajectories of the droplets are investigated considering a turbulent round jet model during exhalation. Aerosols are found to be spreading over distances of 8 to 9 m which is quite alarming. Large droplets get converted to smaller ones but the viral loading of the large droplets is much higher than the smaller as viral loading is proportional to initial size. This is highlighted by the viral load contour and the mean diameter line contour for a half-height window. Different weather conditions are investigated to observe the evaporation of droplets and the formation of aerosols in order to qualitatively analyse the risks associated with each city in specific weather conditions. Hot and dry conditions are most favourable to aerosol formation.

1. Introduction

The outbreak of COVID-19 happened in late 2019 and within six months, the entire world was threatened by the disease. All the countries experienced disruptions in normal life including lockdown of varying extents and periods but the lockdown affected the economy. Thus, relaxation of the lockdown became unavoidable and with the relaxation of lockdown, the count of COVID-affected persons increased sharply. Even after significant reduction in new infections, there have been instances of recurrence of the pandemic through second and even third waves in many parts of the world. Many countries, which had returned to normalcy to a great extent, have been forced to go into extended lockdowns again. Although aggressive vaccination programmes have begun in most of the countries, the protective actions of vaccines are expected to remain effective for finite period of time after administration of a dose. Moreover, the effectiveness of the different vaccines is also not conclusively established. Thus, medical experts are strongly advising against any dilution in basic preventive measures like use of protective masks, maintenance of hand hygiene and social distancing at least for the next several months till the vaccination programme has covered a significant fraction of the community. It has been found out that the SARS-CoV-2 virus transmitted via respiratory droplets and possibly aerosols that are exhaled during speaking, sneezing or coughing [1]. The role of aerosols in community transmission of SARS-CoV-2 virus has been one of the most debated public health issues in recent times. Once the droplets are exhaled, the droplets follow a trajectory depending on the ambient velocity conditions. Moreover, the liquid droplets will experience a reduction in their size due to evaporation of water from the surface of the droplets or they can experience an increase in their sizes due to condensation owing to the ambient humidity and temperature. During the process of exhalation, a droplet cloud is generated which contains a large range of droplet sizes as mentioned in the work of Xie et al. [2]. The local airflow will affect the movement of this droplet cloud. In the droplet cloud, the droplet diameter ranges from 5 μm to hundred microns and they are present by maintaining a probability distribution. The large-sized droplets have a tendency of settling on to the surfaces but the small-sized droplets such as those with diameters around 10 μm tend to evaporate completely before settling. Wells

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provided a study showing the time interval spent by the droplets in the air before settling or evaporation [3]. Xie et al. modified the work of Wells with the inclusion of air velocity, relative humidity (rh) and respiratory jets [4]. Complete evaporation of the small-sized droplets leads to the formation of droplet nuclei which are termed as aerosol. Aerosols, being very small sized particles, remain in the air for a sufficient amount of time and they increase the risk of exposure to the disease. If the aerosols reach the nose, mouth or eyes of a healthy person, the disease will spread directly. Indirect way for the disease to spread is that, if a healthy person touches the surfaces on which the larger droplets have a size distribution and this modality of aerosol size distribution is reported by Reddow et al. [5]. The evaporation of airborne sputum droplets expelled from human cough was modelled by Reddow et al. [6]. A work regarding the study of the effect of turbulence on the droplets was reported by Wei et al. [7]. A multicomponent Eulerian-Lagrangian approach was used to model the evaporation of cough droplets under inhomogeneous humidity conditions by Li et al. [6]. Ventilation becomes an important criterion in the spreading of droplets and to study the effect of indoor air, a numerical study was conducted by Zhao et al. [9]. There are also other works where the exhalation is studied, the evaporation and dispersion from coughing is investigated, the airflow jet dynamics is studied in detail [10-13]. With the onset of the pandemic, research groups from all over the world investigated the droplet evaporation dynamics and the droplet trajectories under different conditions. Several studies have been reported regarding the droplet transmission during coughing and the efficiency of face masks [14,15]. Zhao et al. studied the effect of weather conditions on the propagation of the respiratory droplets and reported that the maximum droplet spreading distance is less in hot and dry regions but the aerosolization rate is maximum in those regions [16]. Droplet trajectories are influenced by the thermal condition of the surroundings. Liu et al. utilised an integral model of expiratory jet to model the evaporation of exhaled contaminants in stratified environments [17,18]. Zhou et al. investigated the lock up height in a thermally stratified environment [19]. A simplified approach was adopted by Cheng et al. [20] to model the trajectories of large respiratory droplets in an indoor environment and it was found that the large respiratory droplets fall within a range of less than 1 m in case of coughing whereas the smaller droplets reduced to aerosol size and they remained suspended in the air [20]. A review article was published by Mao et al. highlighting the physical spreading process of the respiratory droplets and the risk associated with the spread [21]. All these works have focussed on the droplet spreading distance neglecting the formation and trajectories of aerosol. Most of the works have considered the droplet as a pure water droplet which in reality is not true because the expiratory droplets are loaded with salts and pathogens. A few works have been reported where the formation of aerosol has been considered but not the path of the aerosol. Netz modelled the droplet evaporation considering non-volatile solutes dissolved in the droplet and further studied the viral loading in the droplets [22]. Chaudhuri et al. investigated the role of the respiratory droplets in this pandemic by splitting their study in two parts: a) calculating the growth rate of the infection in the population considering the collision and the droplet lifetime and b) modelling the droplet evaporation considering a salt solution and finally, crystallization [23]. But in this work, trajectories of the droplets were not studied. Asadi et al. studied the emission of aerosol through speaking and the variation in aerosol emission due to the randomness of the person while speaking [24]. Aerosols are emitted via the expiratory droplets owing to a size distribution and this modality of aerosol size distribution is reported by Johnson et al. [25]. Numerical modelling of aerosol formation and droplet dispersion has been reported where the hypothesized aerosol transmission has been taken into account and a 3D modelling has been performed by keeping in mind a general public place [26]. It was found that aerosols can be transmitted over distances of 10 m but in this work, pure water droplets have been considered. Airborne transmission has claimed significant attention recently regarding the risk and spread of the virus. Balachandar et al. has worked on the social distance guidelines by using a model for the time evolution of droplet or aerosol concentration in different environments [27]. Aerosol persistence in the air plays an important role in the transmission of the disease which can be modelled using the simple droplet evaporation model [28]. A few other works have investigated the airborne transmission and the influence of wind and relative humidity on the airborne transmission [29-36]. Previously the social distancing norm of 0.8 to 1.3 m was suggested without considering the surrounding air flow and the influence of relative humidity [37]. None of the works have considered complete constituents of the droplet and at the same time, the formation of aerosol along with the trajectories of droplet and aerosol. Also, the effect of the polydispersity of the respiratory droplets on spread of droplets in different surrounding conditions has not been investigated. Two contradictory facts have made the role of aerosols in transmission of the disease. On one hand, unlike larger droplets, which quickly fall to the ground, aerosols remain suspended in air for a long time, making them more potential carriers of virions. On the other hand, the small size of the aerosols implies that their viral loads are also much smaller than the larger droplets. Since the virion content is proportional to the volume of the droplet, a reduction of droplet size by a factor of 10 would imply a reduction of the viral load by a factor of 1000. Thus, it has been argued that the viral load in individual aerosols may be sufficiently low to pose a serious threat of infection. However, this argument holds good only for bioaerosols that have been originally produced with a small diameter during an expiration event like sneezing, coughing, speaking or even breathing. The originally larger droplets can also shrink to the size of aerosols due to the evaporation of the water in it, leaving behind much smaller droplet nuclei. However, the viral load remains at their original pre-evaporation level [22]. This makes the droplet nuclei small enough in size to remain suspended in air for a long time and at the same time carry a sufficiently high viral load to cause infection. Thus, the aerosolized droplets (droplet nuclei) can pose a very serious threat for community transmission and would require serious consideration in devising standard operating procedures for post-lockdown scenarios. The importance of aerosolized droplets has only very recently received serious attention [21,38-40]. The crucial factor in the formation of these suspended droplet nuclei is the ability of the droplets to evaporate to the sizes of aerosols before falling to the ground. The evaporation time, however, is a strong function of the ambient conditions, especially the ambient temperature and the ambient relative humidity. In the present work, we have presented a simple framework of droplet evaporation that takes into consideration the effects of droplet composition and we have tried to correlate the droplet dynamics with the viral load. We have considered several representative climatic conditions to obtain realistic pictures. Both winter and summer conditions have been considered. Considering the global threat of the pandemic in both hemispheres, both winter and summer conditions may be of contemporary relevance. Moreover, the findings of the study are fairly general and applicable to other airborne viral infectious diseases also.

2. Mathematical model

2.1. Droplet path

Droplet tracking is a significant task in order to investigate the maximum spread. In case of speaking, the droplets are released with an initial velocity of 4 m/s [11,41]. In this work, it is assumed that the initial velocity is only in the streamwise direction. The trajectories of the droplets are found out in a Lagrangian framework using the displacement equations considering drag [42].

2.2. Evaporation dynamics

The instantaneous diameter of a droplet depends on the temperature
and humidity of the surrounding atmosphere. Mass transfer from the droplet to the atmosphere takes place due to evaporation and hence, the droplet diameter changes according to the following expression adopted from the work of Abramzon and Sirignano [43]. The existence of non-volatile substances in the droplet affects the evaporation dynamics of the droplet. The presence of solutes suppresses the vapour pressure at the surface and the modified vapour pressure at the surface can be expressed by Raoult’s law [42]. Phase equilibrium is modelled using Clausius-Clapeyron equation.

The initial temperature of the droplet is always a finite temperature above or below the ambient temperature and gradually after the release of the droplets, the temperature reduces or increases depending on ambient temperature. The droplet once released in the air, starts to undergo convection as well as radiation. Moreover, the droplet evaporates which implies that a certain amount of water at the surface of the droplet extracts heat from the droplet which is used as the latent heat of vaporization by that amount of water to get converted into vapour in the atmosphere. Therefore, the reduction in the energy of the droplet owes to these three effects [16].

2.3. Aerosol formation and tracking

Droplets released from the mouth of a person widely vary in composition depending on factors like age and health of the individual and also the activity during which it is released. Following a widely adopted practice in literature (e.g., Wang et al. [2], Zhao et al. [44], Wei et al. [7] Xie et al. [45], Chaudhuri et al. [23]), the droplets have been assumed to be NaCl solutions in water. This is consistent with the recommendations of WHO also [46]. The rationale for the choice of surrogate droplet in the study has been elaborated in the Supplementary Information. As the water evaporates, the salt concentration grows which finally becomes a crystal and this is termed as aerosol. The growth rate of crystal and the rate of change of crystal mass is modelled by the following single step crystallization kinetics [47-49] and is detailed in the Supplementary Information.

After the complete depletion of the mass of the water from the droplet, the virus gets entrapped in the salt crystal which is known as droplet nuclei or aerosol. As the length scale of the aerosol is below 10 μm, buoyancy effect is included in the displacement equations [6].

2.4. Turbulent round jet model

The turbulent round jet model is a well-established model which has been used in many studies of droplet exhalation during coughing and sneezing [6,7]. Here, this model is going to be used for speaking. The round jet model has been considered for both the air flow in the jet as well as the surrounding areas. The semi-empirical root mean square velocity fluctuation and turbulent dissipation profile are derived from CFD modelling [7].

2.5. Calculation of viral load

The viral loading in a droplet primarily depends on the size of the droplet and the total viral loading in a droplet cloud due to a particular size droplet depends on the probability of that droplet in the cloud. The viral loading of a certain droplet size is calculated as follows [22],

\[ N_{\text{vir}} = \frac{\pi d^3}{6} \min(T_{\text{vir}}, T_{\text{dil}}) s_{\text{drop}} \text{c}_{\text{vir}} \]

The droplet production rate is around 10^3 s^-1 and for a specific size of droplet, the droplet production rate is multiplied by the probability of that droplet occurrence to evaluate the droplet generation frequency. The size distribution of the droplet is adopted from the work of Xie et al. [2]. Concentration of virions in saliva is estimated from the viral RNA concentration in human sputum which is approximated to 10^6 ml^-1 [22,35,46,50,51]. Based on the observations of [52] and results obtained by us using the formulation of [53] for viral decay, we have considered the viral load to remain constant as the virion half life is much larger than the time scales for transport and evaporation of droplets.

The model details and validation are provided in the Supplementary information (Fig. 1). The equations are solved by 4th order Runge-Kutta method, using “odeint” function in Python.

3. Results and discussions

3.1. Droplet evaporation

According to the droplet evaporation model presented in this work, we have studied the reduction in droplet size with time. The initial droplet temperature is 306 K and the initial salt concentration in the droplet is 0.01%. Dynamics of surrounding air as well as turbulent jet have not been considered while studying the evaporation of the droplets. Evaporation of water from the droplet surface depends on the partial vapour pressure on the surface of the droplet which is influenced by the surface temperature of the droplet. The surface temperature of a droplet is determined by the heat transfer including phase change between the droplet and the surrounding air. A droplet can completely evaporate, partially evaporate and attain a stable size or it can undergo condensation reaching an equilibrium. Thus, different surrounding conditions can have drastic effects on the droplet. Different surrounding conditions have been considered in our study: a) 293 K 75% relative humidity, b) 313 K 75% relative humidity, c) 303 K 75% relative humidity, d) 303 K 60% relative humidity e) 318 K 75% relative humidity and f) 303 K 90% relative humidity. We are not including dynamic situations in case for evaporation investigation because later on we will see that the larger droplets will settle on the ground prior to evaporation. After settlement on ground, diameter reduction is a complex phenomenon as droplet evaporation dynamics depend on the ground surface [54-63]. The influence of ambient temperature and relative humidity has been studied for 10 μm and 50 μm droplets respectively. The ambient temperature is fixed at 303 K and the relative humidity is varied as 60%, 75% and 90%. With the increase in relative humidity, the evaporation time of the droplets increases and it is inevitable because the rise in relative humidity causes an increase in the saturation vapour pressure in the surrounding which reduces the driving force and thereby inhibits the evaporation. Moreover, with the increase in evaporation time, the final size of the droplet increases. This can be attributed to the fact that when the relative humidity increases, the amount of water leaving the droplet surface is restricted and the final water content at a higher relative humidity environment is more.

The residual amount of water contains the crystal whose size is then comparable to the residual droplet size. Fig. 1c and d show the effect of temperature on droplet evaporation. Here, the relative humidity is kept fixed at 75% and the temperatures are 293 K, 303 K and 313 K. The first thing which can be observed is that the residual droplet size at all the temperatures is equal and this is because the residual water amount in the droplet is decided by the relative humidity and relative humidity being constant, the water amount is the same. Higher temperature encourages faster evaporation as the surrounding environment will supply latent heat to the droplet to help evaporation and also, the surrounding environment with higher temperature has more water holding capacity than the surrounding environment with low temperature. At lower temperatures like 293 K, the droplet evaporates by utilizing its own surface heat and there is no further supply of latent heat from the surrounding environment as the ambient temperature is lower than the initial droplet surface temperature. A few more ambient conditions are presented in Fig. 1e and f. We can observe a similar kind of trend. Higher relative humidity slows down the evaporation rate and restricts the
amount of water leaving the droplet surface which increases the residual droplet size. Fastest evaporation for both the droplets can be seen at 318 K 60% relative humidity and the slowest evaporation is at 293 K 90% relative humidity. High temperature-low humidity is an ideal condition for droplet evaporation because the high temperature environment will be a source of latent heat and low relative humidity will imply more water holding capacity and thus favour the evaporation. If we compare the two droplet sizes, the 10 μm droplet evaporates faster than the 50 μm droplet whatever the ambient condition is. Larger droplets experience a delay in the evaporation time scale due to their larger volume to surface area ratio. A larger droplet implies that the salt crystal will also be larger and this is why the residual droplet size is different for different initial-sized droplets.

It is seen that the droplets take an appreciable amount of time to evaporate completely and before the complete evaporation, many droplets settle on the ground. So, for some droplets the settling time is less than the evaporation time and, in some cases, the evaporation time is less than the settling time. Therefore, it is needed to show the comparison between the settling and evaporation time of the droplets which is presented easily by the Wells evaporation-falling for a dynamic environment in Fig. 2. Model I represents the droplet evaporation model including salt solution and crystallization (which resembles sputum

![Fig. 1. Effect of ambient temperature and relative humidity on evaporation of 10 and 50 μm droplets.](image-url)
reasonably) and model II indicates the evaporation model without crystallization or in other words pure water evaporation model. Four ambient conditions are considered to investigate the result of both the models. For 90% relative humidity (Fig. 2a), model II encourages faster evaporation of the droplets than model I. Increase in water salinity decreases the rate of evaporation due to the reduction of water vapour pressure at the droplet surface. Moreover, crystallization plays a vital role in droplet evaporation because formation of crystal changes the solute concentration inside the droplet which influences the mass transfer rate of water from droplet to the atmosphere. Water leaving the droplet surface increases the solute concentration and when the mass fraction of solute reaches a threshold value of 0.393, crystallization begins. The beginning of crystallization means that a part of the solute concentration is being used up in the formation of crystals. Thus, the droplet always tries to reach an equilibrium position in which no further evaporation takes place, crystal size is then comparable to the droplet size. Pure water evaporation is faster as there is no other entity.

The difference in these two models can be noticed only in case of evaporation. There is no such difference in the settling time as the settling time is primarily governed by buoyancy and gravity. Another observation which can be made from the figure is that model II encourages evaporation of larger droplets compared to model I such as for 313 K 90% relative humidity, model I allows complete evaporation up to 45 μm droplet whereas model II allows complete evaporation of up to 60 μm droplet before settling. Increase in temperature promotes faster evaporation of droplet for both the models. For 60% relative humidity (Fig. 2b), similar observations are noted. The curves of 60% relative humidity have shifted upwards entirely because 60% relative humidity favours evaporation and due to this, lesser time is required for both the models. As time required is less, the difference between the two models has also reduced but there is a significant difference between the models.

3.2. Viral loading and mean diameter

An important thing in case of the respiratory droplets is the viral load in the droplets. The viral loading of the droplets is proportional to the cube of the diameter of the droplets. Thus, a larger size droplet carries more viral loading than smaller droplets. Following the viral loading distribution as mentioned in the calculation of viral load, viral loading contours are presented in Fig. 3 under local conditions of 283 K 85% relative humidity (Fig. 3a) and 313 K 30% relative humidity (Fig. 3b). Along with viral loading, contours of mean diameter are shown for the above atmospheric conditions. The mean diameter is shown by contour lines whereas the viral loading is presented by filled contour. The window considered here corresponds to the half-height situation vertically (0.8 m–1.75 m) and 0–5 m in streamwise direction. The person is
Fig. 4. Number fraction distribution of different diameter droplets shown for different weather conditions. Sub-captions show the varied parameter and the legend for each distribution presents the initial diameter of the droplets.
speaking continuously and after a steady flow has developed, the viral loading and the mean diameter contours are evaluated. The droplets are generated at a frequency of 100 Hz. The mean diameter contour conveys a picture of the droplet diameters present at a specific location and if we compare this picture with the viral loading contour, we will be able to understand which droplets are carrying what amount of viral loading.

(b) Temperature variation

Fig. 4. (continued).
The viral load for both the conditions is almost similar because the trajectories of the droplets are not drastically affected by atmospheric conditions. So, from the mean diameter contour, if it is found that some of the small droplets are carrying the same viral load which is carried by large droplets. The situation becomes alarming as it implies that larger diameter droplets have been converted into smaller droplets. The viral load for both the conditions is almost similar because the mean diameter contour of Fig. 3a, it is seen that the diameter decreases from left to right as vertical is evident from the trajectories of the droplets as the smaller droplets try to cover a larger distance compared to the larger droplets. At a vertical distance of 1 m and stream wise distance of 4–4.5 m, it is found that an average diameter of 15 to 30 μm is carrying a viral load of 5000 to 10,000. Now, when we look at the mean diameter contour of Fig. 3b, the viral loading of 5000 to 10,000 at those specific locations is carried by droplets of size 5 μm. This indicates that the droplet diameter has reduced in case of 313 K 30% relative humidity and it is a major concern because the small droplets of 10 μm size are carrying the same viral load as 25 μm droplets at 283 K, 85% relative humidity. This situation can also be witnessed at locations containing viral loading of 20,000–40,000 such as vertical height of 1 m and stream wise distance of 2.5 m. For 313 K 30% relative humidity, the viral loading is carried by a mean diameter of 25 μm whereas for 283 K 85% relative humidity, the mean diameter of 40 μm is carrying the viral load. Thus, cold and humid condition is not allowing droplet evaporation unlike hot and dry conditions. So, hot and dry conditions pose a threat in transmission of the viral load through small sized droplets.

3.3. Aerosol and safe distance

A situation becomes dangerous when a larger diameter droplet has been transformed to a droplet size of less than 10 μm but carrying an appreciable amount of viral load. These types of situations need to be noticed and, in this work, these situations are highlighted with the number fraction of 10 μm droplets in a particular situation. Now, these particulate matters of diameter 10 μm have been found to be responsible for the spread of the SARS-Cov-2 [64]. Moreover, the efficiency of face covers depend on aerosol size and it has been reported that the droplet and aerosol sizes of less than 10 μm provide some limitation to the mask efficacy [65,66]. Thus, we have tried to separate out the 10 μm diameter droplets from the rest of the droplet cloud in order to identify the relatively safe and dangerous places and seasons. In order to investigate the situations, a person is assumed to be speaking continuously and the droplet distribution is observed at a time instant when the flow has been established and the flow has become steady which implies that the droplet distribution will remain the same at any time instant. We have made an attempt to present the droplet situations in different weather conditions for the different cities. The different weather conditions are as follows: a) the temperature is fixed at 303 K and the humidity is varied as 50%, 60%, 75%, 85% and b) the relative humidity is fixed at 85% and the temperature is varied as 283 K, 293 K, 303 K. Fig. 4a shows the relative humidity variation and Fig. 4b shows the temperature variation. In Fig. 4a, it is observed that the 41 to 50 μm droplets are entirely converted to droplet size of less than 10 μm for 50% relative humidity. As the relative humidity increases, the number fraction of 10 μm droplets at 5 m streamwise distance decreases. This is supported by the discussion in the droplet evaporation section where it was presented that the droplet evaporation decreases with the increase in relative humidity. The droplet classes which are not present in the figure imply that they have crossed the half-height level. Dry conditions are more susceptible to aerosol formation increasing the risk of transmission. In Fig. 4b, with increase in temperature, the number fraction of 10 μm droplets increases. A droplet evolution pattern has been presented in Fig. 4b where the droplet situations at different streamwise distances are shown for 293 K 85% relative humidity. At 5 m streamwise distance, 1 to 10 μm droplets are present in their original size class where as some of the 51 to 60 μm droplets have evaporated to droplets of lower size class, some of them are still present in their original class and some have left the half-height zone. The larger droplets of size 91 to 100 μm have left the half-height zone at 5 m streamwise distance. The number fraction of 10 μm droplets or aerosols are described in detail in the next discussion.

In the following discussion some cities are referred to as examples and the location of these cities can be found in the Supplementary information along with their weather conditions. As we have already discussed that PM10 plays a significant role in the transmission of diseases related to respiratory droplets, we tried to investigate the variation of number fraction of PM10 with ambient temperature and relative humidity. The investigation of PM10 is carried out at a streamwise distance of 2 m from the human body in order to relate our findings to the Social Distancing norm of 2 m. From the contour plot in Fig. 5a, the number fraction of PM10 is found to be increasing with increase in temperature and decrease in relative humidity. This result is evident from the previous discussions where we have seen that with increase in temperature and decrease in relative humidity, droplet evaporates at a faster rate and hence, droplet nuclei formation is faster. The role of low relative humidity in promoting the spread of diseases through air-borne pathogens has also been discussed by Bozic and Kanduc [67]. With decrease in temperature and increase in relative humidity, droplet evaporation is slower which causes a hindrance to the aerosol formation and as a result, PM10 number fraction is low. On the contour plot, the cities with their corresponding weather conditions are shown. Jaipur Summer is most prone to the formation of PM10 and hence it has the highest risk of transmission by the aerosol route. Winter in Shillong can be considered to be the safest in terms of PM10 formation. Formation of PM10 occurs when a larger diameter droplet has undergone reduction in size due to evaporation leading to the formation of droplet nuclei. Thus, PM10 may contain the viral loading of a large droplet which will never be equal to the viral loading of a small size droplet as it is evident from the viral loading calculation. A contour plot of viral loading based on PM10 concentration at a stream wise distance of 2 m is presented in Fig. 5b. The figure is providing with the information that a high viral load is witnessed in hot and dry conditions because the high temperature and low relative humidity encourages the larger droplets to evaporate and transform to PM10. But the cold and humid condition is not allowing the larger diameter droplets to evaporate fast and hence, the viral loading in those conditions is low. From these two figures, it can be inferred that the 2 m social distancing norm of 2 m may be inadequate especially in hot and dry conditions because PM10 being very small in size can penetrate through face protective masks and can cause fatal infections as they will be carrying the viral load of a larger diameter droplet such as 40 μm.

Investigation of a safe distance (L_safe) is crucial as it will be different in different weather conditions. A stream wise distance is considered to be safe when 80% of the droplets have left the half-height window of 0.8 m in the transverse direction. In this investigation, we have considered the dynamics of the aerosol and correspondingly, a contour plot of L_safe is shown in Fig. 5c. It can be noticed that in hot and dry conditions L_safe is more compared to the cold and humid conditions. This nature of the contour can be attributed to the aerosol dynamics. In hot and dry conditions, aerosol formation is more prevalent and as aerosol has less inertia, they are carried away by the local air jet further away from the mouth. In contrast to hot and dry conditions, in cold and humid conditions aerosol formation is inhibited due to which the droplet does not undergo mass reduction which causes the droplet to leave the half-height window early. This aerosol dynamics can be observed in the curves presented in Supplementary information (Fig. 2). Aerosol of 50 μm is spread over a large distance when the temperature is high and the relative humidity is low. This spread is represented by L_safe in the contour. Barring summer conditions in Jaipur, for all the other cities an average streamwise distance of 5 m can be considered as L_safe. By considering this distance, a viral load contour is presented in Fig. 5d.
The variation in the contours is similar to the variations seen in $L_{\text{safe}}$ contour. Viral load is high in hot and dry conditions and the viral load decreases with decrease in temperature and increase in humidity. The viral load at 5 m is more than the viral load of PM10 at 2 m presented in Fig. 5b. This is because, in Fig. 5b, the stream wise distance is 2 m and at that distance the larger droplets like 50 or 60 $\mu$m have not evaporated to PM10. But in Fig. 5d, at 5 m we are considering the viral load of all the droplets which are present. The significance of the role of aerosolized droplets in the transmission of the disease, as revealed here, can have serious implications in the standard operating procedures to be followed. The efficacy of many grades of non-medical masks, being used by a large section of the population, against aerosols has not been clearly established. However, our study highlights the danger posed by the larger droplets evaporating to significantly smaller sizes. Thus, the small droplet nuclei are posing major risk at the point of inhalation rather than at the point of the exhalation. At the source, these droplets are large enough to be effectively filtered by the non-medical grades of two layer or three layer masks. Even designs of multilayer home-made masks, made of a layer of hydrophilic material sandwiched between two hydrophobic layers have been shown to be effective at the exhalation point [68]. Thus, a high compliance of compulsory mask use policy can be sufficient.

The safe streamwise distance has been investigated above by considering the aerosol dynamics but generally in most of the literature, the safe distance is calculated without considering the aerosol route of transmission. Since the role of aerosols in transmission of virus has not been conclusively proved, we have also estimated safe distance $L_{\text{safe}}$ without considering aerosol dynamics. The contour of $L_{\text{safe}}$ is presented in Fig. 5e. In this figure, the safe distance is considered to be the axial distance at which 80% of the droplets have either fallen below the half height or has been converted to aerosol. The variation with temperature and relative humidity is opposite to that of Fig. 5c. Here, low temperature and high humidity experiences the maximum $L_{\text{safe}}$, like the cities of Kolkata and Pune. This nature of variation can be explained by the trajectories presented in Supplementary information (Fig. 2). If we focus on the 50 $\mu$m curves of 303 K, we can see that the 50 $\mu$m droplet evaporates completely at a distance of around 3 m before achieving half-height at 60% relative humidity whereas the droplet leaves the half-

Fig. 5. Contours of a) PM10 number fraction at 2 m, b) PM10 viral load at 2 m, c) $L_{\text{safe}}$ with aerosol dynamics, d) Viral load at 5 m, e) $L_{\text{safe}}$ without aerosol dynamics and f) Viral load at 3 m. Legend contains cities and their respective weather conditions; J-Jaipur K-Kolkata P-Pune S-Shillong T-Thiruvananthapuram S-Summer M-Monsoon W-Winter.
height window approximately at 3.5 m streamwise distance when relative humidity is 75%. When the relative humidity is 90%, the droplet leaves the half-height zone around 2.8 m. So, 75% relative humidity experiences the largest spread. This is because, the droplet at 75% relative humidity evaporates faster compared to 90% relative humidity and due to the light weight at lower relative humidity, the droplet covers a larger streamwise distance. Now, if we look at the curves of 293 K, we can observe that the 50 μm droplet covers a larger distance at low relative humidity than at high relative humidity values. The complete evaporation of 50 μm droplets at 293 K occur after leaving the half-height zone and therefore, the droplets are reduced to smaller sizes and are carried away by the local air jet. Smaller the size, larger is the streamwise distance covered by the droplet and the size is related to the ambient relative humidity. If the complete evaporation occurs much before half-height level, the droplet will not be able to cover a large distance. The fact is evident if we fix the relative humidity value and look at the curves of 293 K and 303 K. The 50 μm droplet at 303 K 60% relative humidity evaporates faster and hence, the spread is very less compared to 293 K 60% relative humidity. But for 75% relative humidity, 303 K experiences a greater spread than the 293 K because, 303 K encourages evaporation of the droplet and due to this, the droplet size reduces and gets carried away by the local air which is not so in the case of 293 K. At 293 K, droplet evaporation is slow which does not allow mass reduction and due to the inertia, the droplet leaves the half-height window at a less distance. Therefore, at half-height level, a competition is going on between evaporation and gravitational acceleration. From the contour of Fig. 5e, we can see that Kolkata and Pune will experience the maximum Lsafe if we neglect the aerosol dynamics. Similarly, a viral load contour is presented in Fig. 5f. The distance of 3 m is considered for the viral load presentation as it appears to be the average Lsafe for the cities. The viral load contour presents the similar result of Lsafe contour. From both the contours of Lsafe in Fig. 6c and 6e, it can be concluded that Lsafe is definitely dependent on ambient conditions and a particular Lsafe of 2 m can never be adjudged for all weather conditions. The picture of Lsafe with aerosol dynamics is just the reverse picture of Lsafe without aerosol dynamics. This information is very significant as aerosols are claimed to be spreading infections and increasing the risk of transmission. In this explanation, formation of aerosol before half-height is considered to be safe.

4. Conclusion

In this work, a detailed evaporation model including crystallization is investigated with the influence of ambient temperature and relative humidity. The evaporation model was then combined with the droplet and aerosol trajectory model to develop a simple but realistic model of dynamics of droplets released from the mouth. This scenario is demonstrated for different Indian cities representative of different weather conditions in order to find out the most dangerous situations in terms of droplet spreading distance, aerosol spreading distance, PM10 number fraction and viral load.

Pure water droplet evaporates faster than the salt solution droplet whereas the formation of crystal further delays the process of evaporation. Evaporation of droplets reduces the size of the droplets and finally aerosol formation takes place. Aerosols can travel up to large distances of 9 to 10 m in stream wise direction as they are carried by the surrounding air jet and they are unable to detach themselves from the jet. Evaporation is appreciably affected by the ambient temperature and relative humidity. Low relative humidity encourages the mass transfer of water from the droplet surface to the atmosphere. If the ambient temperature is higher, the local environment becomes a heat source for the droplet and supplies the latent heat to the droplet for further evaporation. Larger droplets which get reduced to small size droplets, are carried away large distances by the local air due to their low inertia and this causes a change in trajectory with change in ambient conditions. The small sized droplets and the very large size droplets of 10 μm and 100 μm do not show significant variations in trajectory.

Viral loading is proportional to the cube of the initial diameter of the droplets and it becomes significant when a large droplet has been transformed to a small droplet as it is carrying a higher viral load compared to the droplets which are initially of that small size. The viral loading contour for a high and a low relative humidity situation is found to be almost similar because the trajectories of the droplets are not affected by the ambient conditions. When the relative humidity is low, the larger diameter droplets are found to be converting themselves to smaller diameter droplets but the viral loading remains the same as of a large droplet which is not the case for a high relative humidity situation where the larger droplets are reluctant to get converted to smaller ones. So, for a low humidity situation, the risk is higher because face protective masks may not be so efficient in trapping the smaller droplets and the smaller droplets are carrying the viral load of a larger droplet.

The fraction of PM10 increases in hot and dry conditions and as a result, PM10 in hot and dry conditions consists of higher viral load. This work signifies that respiratory droplets of small sizes pose a threat in transmission of flu type diseases and also, the dynamics of aerosol is pretty significant in case of such transmissions. Although the studies have been done considering a number of Indian cities only, the geographical conditions vary from near equatorial to sub-tropical and a wide range of topologies. Thus, these results can be applicable to many places of the world. Similarly, although the recent pandemic caused by SARS-CoV-2 has been the driving factor for this work, the results can be of relevance to a wide range of diseases transmitted through respiratory droplets.

The results point out significant information regarding aerosol. If aerosol formation and its trajectory is considered, hot and dry weather conditions turn out to be dangerous situations in terms of safe distance whereas if the aerosol trajectory is neglected, cold and humid conditions become an alarming zone for droplet spread. Thus, the situation is dependent on the role of aerosol and a lot of debate is going on regarding the influence of aerosol on the spread of respiratory diseases. So, until and unless, literatures become confident regarding the role of aerosol, transmission risk in case of aerosol cannot be neglected and the health regulatory organisations must make people aware of the hot and dry situations where aerosol spread is the largest.

Credit author statement

Ritam Pal: Data curation; Formal analysis; Software; Validation; Writing - original draft; Visualization. Sourav Sarkar: Investigation; Writing - review & editing; Supervision. Achintya Mukhopadhyay: Conceptualization; Investigation; Writing - review & editing; Supervision.

Declaration of Competing Interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.icheatmasstransfer.2021.105750.

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