Characterization and Dispersion of Human Expiratory Droplets – a Review

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ABSTRACT

The paper reviews studies conducted on human expiratory droplets for the purpose of defining the characteristics of expiratory droplets, their maximum dispersion and the forces influencing that in an unventilated environment. The review shows coughing, sneezing and speaking droplets to have comparable size ranges, while breathing droplets have the narrowest size range. Sneezing droplets have the largest average size and highest velocity among expiratory droplets. Compiled data reveal droplet Froude number offers a plausible quantitative measure of the droplet maximum spread. The fate of the airborne droplets is seen to be dictated by an interplay between their inertial force and gravitational force. The higher the Froude number, the greater is the droplet spread. Small droplets with high flow inertia, such as dry sputum droplets, are capable of reaching longer horizontal distances in comparison to large droplets. The review shows the maximum horizontal distance coughing droplets can reach exceeds 2 m, while sneezing droplets can reach distances above 6 m, greater than the 2 m physical distancing currently adopted to avoid virus contamination.

INTRODUCTION

Human respiratory activities such as coughing, sneezing and speaking generate a wide size range of expiratory droplets (Xie et al., 2009; Chao et al., 2009, Johnson et al., 2011; Duguid, 1946; Gerone et al., 1966; Asadi et al., 2019) that can be pathogen carriers for airborne viruses (Marr et al., 2019; Jayaweera et al., 2020; Das et al., 2020; Seminara et al., 2020; Tang et al., 2013; Zhu & Kato, 2006; Yang et al., 2018). The spread of expiratory droplets depends on several factors such as the droplet size, ejection velocity (Asadi et al., 2019; Tang et al., 2013; Zhu & Kato, 2006; Van Sciver et al., 2011; Wei & Li, 2015; Kwon et al., 2012; Li et al., 2018), droplets concentration and volumetric flow rate (Zhu & Kato, 2006; Yang et al., 2018; Van Sciver, 2011; Li et al., 2018; Gupta et al., 2009), ambient temperature and relative humidity (Wei & Li, 2015; Li et al., 2018; Redrow et al., 2011; Ji et al., 2018). A substantial number of experimental and computational fluid dynamic (CFD) studies (Lieber et al., 2021; Chen et al., 2020; Cheng et al., 2020; Rosti et al., 2021; Zhu & Kato, 2006; Yang et al., 2018; Li et al., 2018; Ji et al., 2018) have been conducted on airborne respiratory droplets. This paper reviews past studies conducted on human expiratory droplets for the purpose of classifying the droplets based on their characteristics (size, ejection speed, flow rate), and determining the conditions influencing the droplets maximum spread in an unventilated environment.

METHODS

Literature review on the characteristics and spread of expiratory droplets was conducted using ScienceDirect, SpringerLink, and Web of Science databases. The review was done on literature published before April 2021, and it focused exclusively on the spread of expiratory droplets in unventilated environments. The search included experimental studies and numerical simulations. Search keywords such as “expiratory droplets”, “exhaled droplets”, “coughing droplets”, “sneezing droplets”, “breathing droplets”, “droplets spread”, “droplets evaporation”, “COVID-19 droplets” and “droplets dispersion” were used in the search.

In the first part of this review, experimental data on the size and the percentage distribution of droplets from different expiratory activities (coughing, sneezing, breathing, and speaking) were extracted from published literature. The droplets arithmetic mean size was then calculated. Data regarding the droplets maximum ejection velocity and peak volumetric flow rate were also extracted.

The second part of the review concentrated on expiratory droplets evaporation and their spread in unventilated environments. The review included a comparison in the evaporation rate between pure water droplets, saline, saliva and sputum droplets as function of relative humidity. Data was retrieved on the droplets horizontal spread as function of the droplets diameter and ejection velocity. This information was then used to calculate the droplets Froude number in order to reveal how the droplet horizontal spread is influenced by two forces: the droplet inertial force and the gravitational force pulling the droplet downward.

CHARACTERIZATION OF EXPIRATORY DROPLETS

Size and Distribution of Expiratory Droplets

During the last few decades, several studies have been conducted on human respiratory activities that include coughing, sneezing, speaking and breathing. Figure 1 shows the size and percentage distribution of respiratory coughing droplets. Data compiled from various studies show the size of coughing droplets can range starting from as low as 0.25 μm and up to 1,500 μm with an arithmetic average droplet size of 64 μm. Xie et al. (2009) conducted a series of experiments using aerosol spectrometer to detect smaller droplets, and glass slides and a microscope to detect larger respiratory droplets from heathy male and female individuals. Slightly larger average droplet sizes were obtained from male individuals when compared to results obtained from females, while the percentage of droplets size distribution was very close. Their coughing droplet size ranged from 7 μm to 1,500 μm. Duguid (1946) used glass slides and a microscope to quantity the respiratory droplets. His coughing droplets size and distribution were comparable to that by Xie at al. Chao et al. (2009) used interferometric Mie imaging technique to measure the droplet size, a technique that allowed measuring the droplets in a close proximity to the mouth in order to avoid air sampling losses. Their coughing droplets size had a comparable range to that of Xie et al., but the percentage of small droplet sizes was much higher than those reported by Xie et al. and Duguid since the system of Chao et al. is optimized for spray investigations of smaller droplets. Johnson et al. (2011) used Aerodynamic Particle Sizer and Droplet Deposition Analysis to measure the size distribution of coughing droplets using a small closed-loop wind tunnel into which the subject head was inserted. Their data show the droplet size distribution had a very narrow range with droplets smaller than 10 μm. Zayas et al. (2012) used a laser diffraction system to accurately determine the time-dependent droplet size distribution of expelled respiratory droplets through a cylindrical measurement zone. Their results show the majority of the coughing droplets were in the sub-micron range, but few droplets as high as 55 μm in size were also recorded.

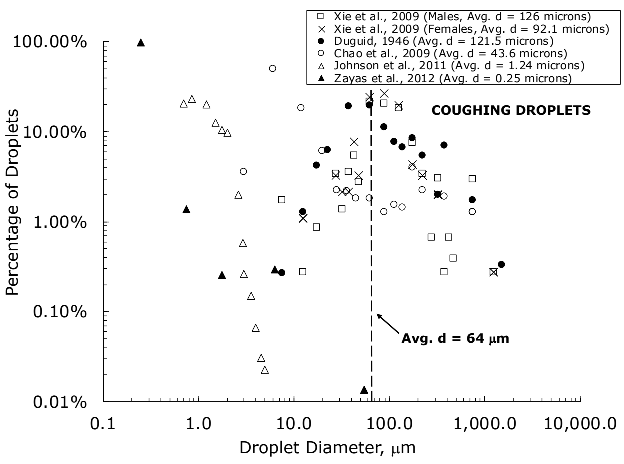

Figure 1. Size range of respiratory coughing droplets

Figure 2 shows the size and percentage distribution of respiratory sneezing droplets. Similar to coughing droplets, the data in Fig. 2 show the size of sneezing droplets ranges from 0.5 μm to 1,500 μm with an arithmetic average sneezing droplet size of 134 μm. Gerone et al. (1966) used a laboratory-type photometer for counting and sizing sneezing particles as the particles pass through an illuminated area. Very fine droplet sizes between 0.5 μm and 11.5 μm were recorded with the majority of these droplets being around 1 μm and lower. This is quite different than the much wider droplet size range that has been reported by Duguid. Han et al. (2013) used a laser particle size analyzer to measure the size distribution of sneezing droplets exhaled immediately at the mouth. Measured results of tested subjects revealed two types of volume-based size distributions of sneezing droplets: unimodal and bimodal. Unimodal distributions had a larger droplets than bimodal distributions along with a narrower droplet size range. Few droplets as large as 940 μm were observed.

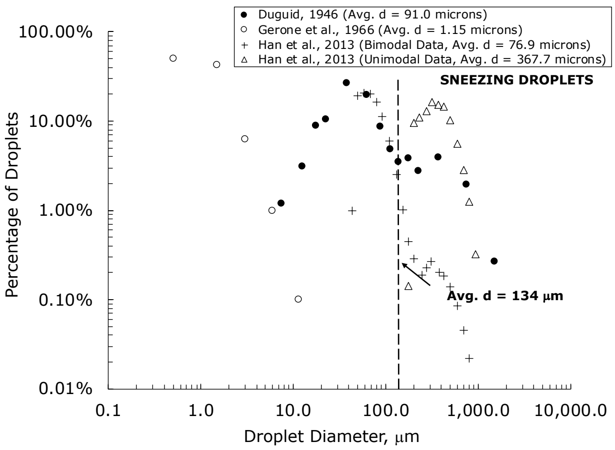

Figure 2. Size range of respiratory sneezing droplets

Figure 3 shows the size and percentage distribution of respiratory speaking droplets. In comparison to coughing and sneezing droplets, data compiled from various resources show the speaking droplets size range remains virtually the same as that of coughing and sneezing droplets. However the arithmetic average sneezing droplets size (52 μm) is smaller than that of coughing droplets. Asadi et al. (2019) used an Aerodynamic Particle Sizer placed in a laminar flow hood to determine the size distribution of respiratory droplets emitted by individuals performing various vocalization activities such as speaking in a loud, intermediate or quite tone. Their results show, the percentage of droplets size and their distribution range remain the same, expect the number of droplets produced during speaking activities increase as the speaking tone gets louder. Asadi et al. results are in agreement with that of Johnson et al. (2011) who also used an Aerodynamic Particle Sizer to measure the size distribution of speaking droplets. Both researchers have their speaking droplet sizes range between 0.6 μm and 7 μm. Again, as was observed for coughing droplets, the results of Xie et al. (2009) and Duguid (1946) are in agreement. Since both of them used micrometry to detect respiratory speaking droplets, similar droplet sizes were detected. Chao et al. (2009)

detected large droplet sizes using their interferometric Mie imaging technique.

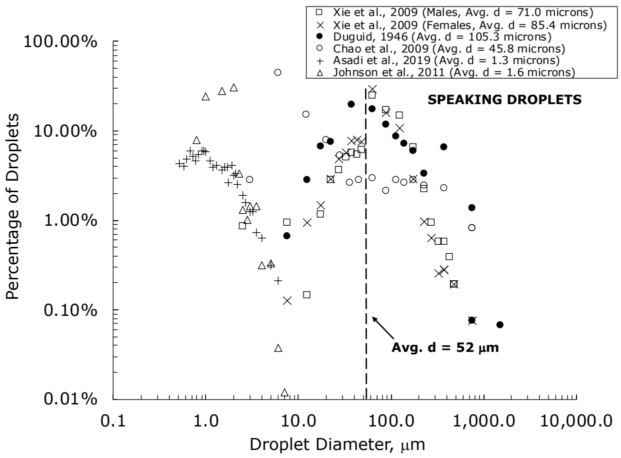

Figure 3. Size range of respiratory speaking droplets

Figure 4 shows the size and percentage distribution of respiratory breathing droplets. These droplets are the smallest of all respiratory droplets. Data compiled from several studies show the size of breathing droplets to range from 0.4 μm to 10 μm. The arithmetic average droplet size in those studies is 0.64 μm. Both Morawska et al. (2009) and Johnson et al. (2011) used Aerodynamic Particle Sizer to measure the size distribution of breathing droplets where the subject head was inserted in a small closed-loop wind tunnel. The size range and the percentage distribution of droplets of those studies were comparable. Fabian et al. (2008) collected exhaled breath from subjects onto teflon filters and measured the droplets concentrations using an optical particle counter. Their results detected a droplet size range that is wider than that of Morawska et al. and Johnson et al., but the percentage of droplets smaller than 0.5 μm was not far off.

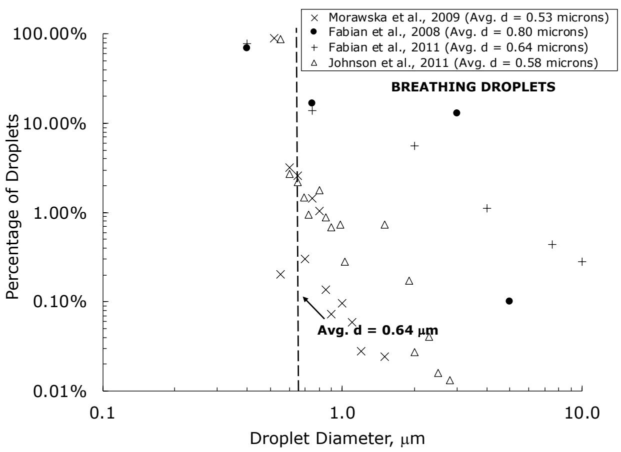

Figure 4. Size range of respiratory breathing droplets

Velocity and Flow Rate of Expiratory Droplets

The velocity of expelled respiratory droplets is very important in predicting the droplets transmission distance. Several researchers have used Particle Image Velocimetry (PIV) to measure the velocity field of exhaled air from coughing (Zhu & Kato, 2006; Van Sciver, 2011; Kwon et al., 2012) and speaking (Kwon et al., 2012). The maximum velocity of coughing droplets reported by these authors is seen to vary from 11 to 29 m/s (Fig. 5). Using a PIV system, Kwon et al. have shown that the maximum velocity of expelled respiratory droplets vary with gender where males subjects are shown to have 44% higher velocities than female subjects. Others, Tang et al. (2013), have used real time shadowgraph imaging to capture high speed images of healthy subjects coughing. Captured imagery shows the expelled coughing droplets to peak around 7 m/s, which is considerably lower than that obtained from PIV measurements. A number of studies have been conducted on modelling the transport and dispersion of coughing droplets (Wei & Li, 2015; Li et al., 2018; Redrow et al., 2011; Zhang & Li, 2012; Zhao et al., 2005; Mui et al., 2009). With the exception for the numerical simulations conducted by Zhao et al. (2005) and Mui et al. (2009) that imposed emission velocities on coughing droplets as high as 100 m/s, the peak emission velocity of coughing droplets used in numerical simulation by the rest of these authors ranged from 8 to 30 m/s, close to what is predicted in PIV measurement studies.

The average peak emission velocity of sneezing droplets is shown in Fig. 5 to be slightly larger than that of coughing droplets. Compiled data from several studies (Zhao et al., 2005, Tang et al., 2013; Rahiminejad et al., 2016; Scharfman et al., 2016; Bahl et al., 2020) show the peak velocity to range from 4 to 62 m/s, except for the study conducted by Zhao et al. (2005) where the peak sneezing velocity was 100 m/s. The peak emission velocity of breathing droplet is seen to be substantially lower than that of coughing and sneezing droplets, ranging only from 1.4 to 6 m/s as studies reveal (Tang et al., 2013; Zhao et al., 2005; Villafruela, 2013). On the other hand, the peak in speaking droplets velocity is seen to be not far off from breathing droplets, ranging from 2.3 to 4 m/s (Kwon et al., 2012) with males having higher emission velocity than female subjects.

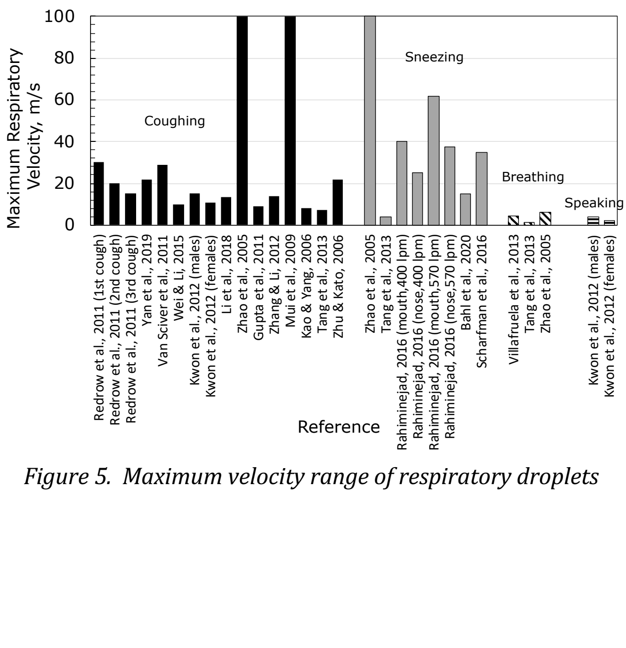

Figure 5. Maximum velocity range of respiratory droplets

Figure 6 shows the variation in the peak flow rate of respiratory droplets between various studies. Coughing droplets exhibit the highest flow rates (Zhu & Kato, 2006; Li et al., 2018; Gupta et al., 2009; Yan et al., 2019; Mahajan et al., 1994; Singh et al., 1995; Lindsley et al., 2013; Zhao et al., 2005; Zhang et al., 2017), followed by sneezing droplets (Rahiminejad et al., 2016), followed by speaking droplets (Gupta et al., 2010) and then breathing droplets (Zhao et al., 2005; Gupta et al., 2010; Ai & Melikov, 2018). Literature review shows limited number of studies conducted on sneezing and speaking respiratory droplets. Coughing droplets peak flow rate is shown to range from 4.2 to 22 l/s, while the study on sneezing reveals a peak flow rate of 9.5 l/s, compared to 1.6 l/s for speaking droplets, and 0.01 to 0.4 l/s for breathing droplets.

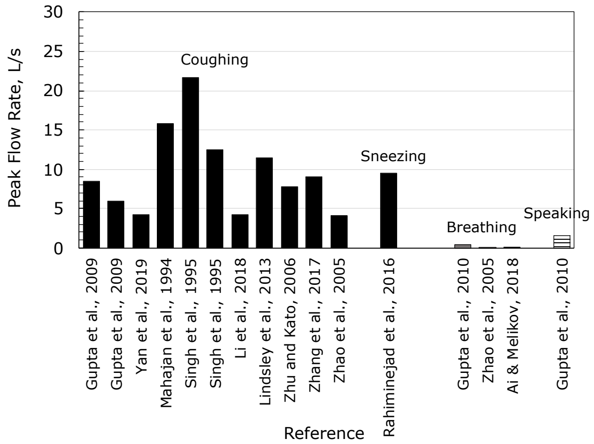

Figure 6. Peak flow rate of respiratory droplets

EXPIRATORY DROPLETS EVAPORATION AND SPREAD

Droplets Evaporation

Redrow et al. (2011) simulated the evaporation of different types of single droplets: pure water, saline and sputum droplets. Sputum droplets had the following constituents: 94.5% water, 1.1% protein, 1.5% lipid, 1.23% carbohydrates, 0.05% DNA and 0.55% salt, while saline droplets consisted of salt and water only. Their results for 50 μm size droplets are shown in Fig. 7. The initial temperature of the droplets was 310.15 K, initial velocity was 10 m/s, and the ambient air temperature and relative humidity were 293.15 K and 80%, respectively. In comparison to the evaporation of a pure water droplet, simulation shows the evaporation rate of a saline droplet to be slightly lower resulting in a 10 μm dry salt residue after approximately 2.5 s, while the evaporation rate of a sputum droplet to be significantly lower due to the effect of the different constituents in the droplet. The sputum droplet reduces to a dry residue close to 23 μm after approximately 10 s. It is those droplets that do not settle quickly to the ground but remain suspended in the air for long durations to be the most harmful in carrying viruses.

Yan et al. (2019) simulated the evaporation of lone saliva droplets having a composition of 98.2% water and 1.8% non-volatile solid compounds. The evaporation of 10 μm and 100 μm saliva droplets are shown for 0 and 90% relative humidity in Fig. 7. The evaporation time, which is driven by the difference between the vapor density at the droplet surface and the surrounding air, is shown to substantially increase with the increase in relative humidity. Simulation shows the initial droplet size to strongly affect the onset of droplet evaporation. This is due to the effect of droplet surface tension. Larger surface tensions are associated with bigger droplet sizes. The larger the surface tension, the longer is the delay in the onset of droplet evaporation.

Kukkonen et al. (1989) simulated the evaporation of freely falling pure water droplets where the influence of droplet concentration on the evaporation process was examined. Figure 7 shows the diameter of a 200 μm water droplet versus time for droplets concentrations of 0.3 and 3 droplets/cm³. For the high concentration of 3 droplets/cm³, simulation shows the evaporation to stop after reaching 30 s. This duration will increase as the droplets concentration increases. Evaporation is shown to terminate as the relative humidity of the gas far away from the droplets approaches saturation condition. For the case of smaller concentration, 0.3 droplet/cm³, droplets completely evaporate before saturation condition is reached.

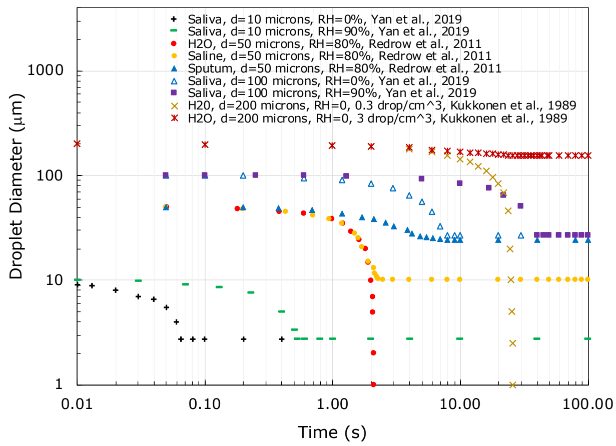

Figure 7. Evaporation of droplets of different types and sizes

Figure 8 shows the evaporation of saliva and water droplets at relative humidity of 0% and 90% and ambient temperature around 18 °C. Droplets are ejected from an elevation of 2 m above ground. At 0% relative humidity (Wells, 1934), water droplets smaller than 140 μm are shown to completely evaporate before hitting the ground. In this case, water droplets larger than 140 μm will reach the ground, and the figure shows the time it takes for that to happen. Water droplets that are 200 μm in size reach the ground in 1.7 s. However for the case of saliva droplets (Lieber et al., 2021), droplets will not achieve complete evaporation. Compared to water droplets, the airborne life time of saliva droplets substantially increases. As the figure shows, a critical saliva droplet size is reached below which the droplet will remain indefinitely suspended in the air (< 60 μm for 90% relative humidity, and < 115 μm for 0% relative humidity).

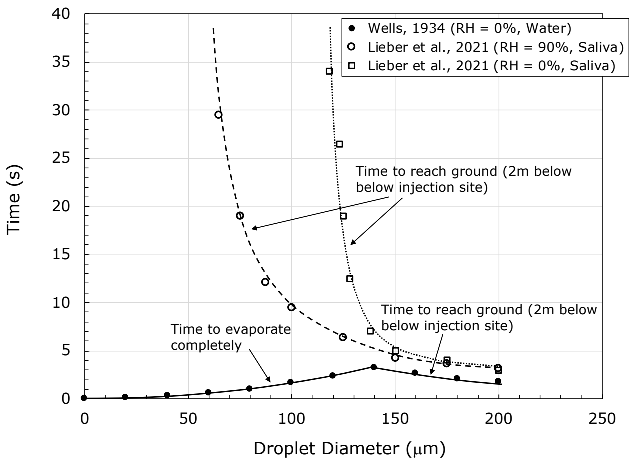

Figure 8. Evaporation of small droplets versus falling time of large droplets (freely falling)

Droplets Horizontal Spread

The maximum horizontal distance respiratory droplets can reach depends on two factors: the droplet initial velocity and diameter. Data compiled from several studies are presented in Fig. 9 showing the droplets horizontal spread as function of the droplet diameter and initial velocity. Data shows sneezing droplets reach longer distances because of their higher initial velocity (Xie & Li, 2006; Bourouiba, 2020). This is followed by coughing droplets that are ejected with relatively lower speeds (Wei & Li, 2015; Ji et al., 2018; Xie & Li, 2006; Bourouiba et al., 2014; Liu et al., 2017; Cheng et al., 2020; Chen et al., 2020; Das et al., 2020; Wang et al., 2020) followed by speaking droplets that have substantially much lower speeds (Teunis et al., 2010; Xie & Li, 2006; Parienta et al., 2011). The case associated with exhaled droplets seen in the simulation by Rosti et al. (2021) resulted in a droplet maximum horizontal reach that was in the range of coughing droplets due to the high ejection velocity (13 m/s) that was used in the simulation. The general trend that the results (Fig. 9) show is that the maximum horizontal distance speaking droplets can reach is close to 1 m, while coughing droplets can exceed 2 m, and sneezing droplets can reach a distance above 6 m. Smaller droplets are shown to reach longer horizontal distances since they can remain suspended for prolonged periods of time in comparison to larger droplets that will quickly fall to the ground. These results are in agreement with a recent study conducted by Rosti et al. (2020). These results show that the 2 m physical distancing that is currently adopted to avoid virus contamination may not suffice, and further studies, particularly experimental studies, need to be conducted. In the current coronavirus disease 2019 (COVID-19) pandemic, the recommendation by the World Health Organization (WHO, 2021) for physical distancing in order to reduce exposure to the virus is specified to be at least 1 m, while that by the Centers for Disease Control and Prevention (CDC, 2020) is set to 1.83 m. It should be noted here that even though this review concentrated only on expiratory droplets flow in an unventilated environment, the presence of natural ventilation can increase the droplet travel distance substantially (Dbouk & Drikakis, 2020; Gorbunov, 2020). Dbouk and Drikakis have shown in their CFD simulation that the travel distance of coughing droplets (10 – 120 μm) will exceed 6 m in a wind speed of 1 m/s and relative humidity of 50%. On the other hand, Gorbunov has shown that 10 μm coughing droplets ejected at a concentration of 5 particles/cm^3, 1 m/s wind speed and 50% relative humidity can reach a distance of 9 m with a detectable concentration at 20% of the initial concentration, and a distance of 36 m with a detectable concentration of 10%.

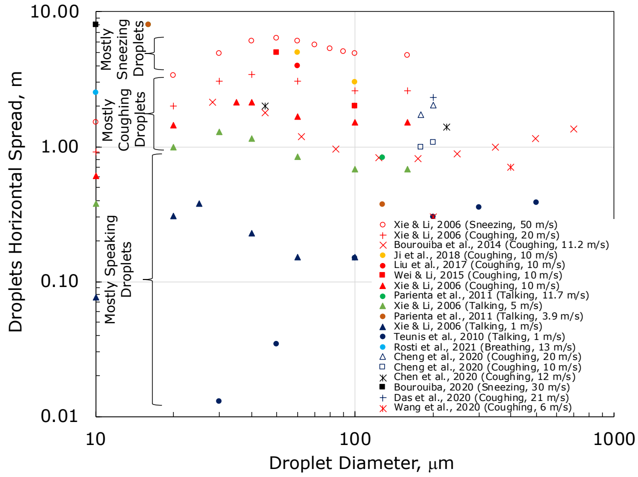

Figure 9. Effect of respiratory droplets size on droplets horizontal spread

The data from Fig. 9 was then utilized to calculate the droplets Froude number for the studies that are presented. Figure 10 shows the droplets horizontal spread as function of the droplets Froude number. Droplet Froude number, *Fr*, is defined as the ratio of the flow inertia to the droplet gravitational force:

$$Fr = V/\sqrt{gD} \quad (1)$$

where:

V is the droplet velocity [m/s], D is the droplet diameter [m], and g is the gravitational acceleration [m/s^2]. The figure clearly shows an increase in the droplet horizontal spread as the droplet Froude number increases. Thus, the fate of the airborne droplets is dictated by the interplay between their inertial force and gravitational force. Large droplets with low inertial force can only cover a shorter horizontal distance. Since the effect of the flow jet velocity on these droplets is small and their gravitational force is high, they can quickly settle to the ground. On the other hand, small droplets with high inertial force can reach a longer horizontal distance since they can get trapped into the jet flow. Because their gravitational force is small, they can remain airborne for longer duration and thus will not settle quickly to the ground. It is those droplets that are most harmful in spreading viruses.

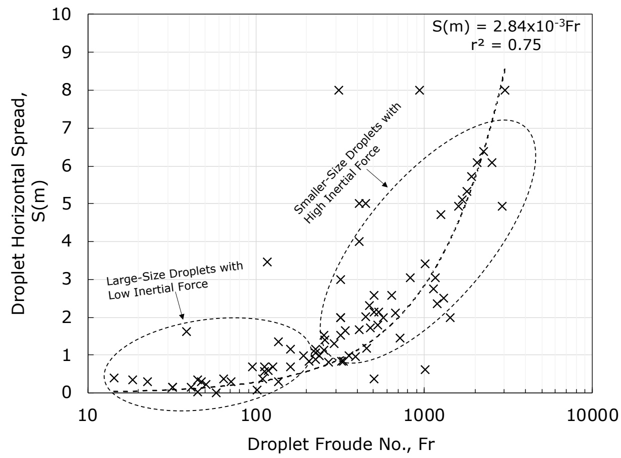

Figure 10. Respiratory droplets maximum horizontal spread as function droplets Froude number

CONCLUSIONS

A review was performed on studies conducted on human expiratory droplets for the purpose of characterizing expiratory droplets and investigating the conditions affecting their maximum spread in an unventilated environment. The following conclusions are reached:

- Coughing, sneezing and speaking droplets can range from sub-microns to 1,500 μm, while breathing droplets have a narrow size range from sub-microns to 10 μm.

- Sneezing droplets have the highest emission velocity peak among all respiratory droplets, followed by coughing droplets, and then by breathing droplets and speaking droplets.

- Coughing has the highest volumetric flow rate among expiratory activities, followed by sneezing, followed by speaking, and then by breathing.

- The initial droplet size strongly affect the onset of droplet evaporation. The larger the droplet size, the longer is the delay in the onset of droplet evaporation.

- Evaporation is influenced by droplets concentration. High concentrations can cause the evaporation to cease quickly.

- The decrease in relative humidity causes the droplets to remain airborne longer, resulting in an increase in the droplets maximum spread.

- Droplet Froude number offers a plausible quantitative measure of the droplet maximum spread. The higher the Froude number, the greater is the droplet spread.

- The fate of airborne droplets is dictated by the interplay between their inertial and gravitational forces. Large droplets with small inertial force can only cover a shorter horizontal distance, while small droplets with high inertial force can spread over a longer distance.

- Studies show that in an unventilated environment, the maximum horizontal distance speaking droplets can reach is close to 1 m, while coughing droplets can exceed 2 m, and sneezing droplets can reach a distance above 6 m.

- The 2 m physical distancing that is currently adopted to avoid virus contamination may not be sufficient.

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