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Physical Characterization and Droplet Dispersion of Sneeze or Cough Ejecta: A Review

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Abstract - P*hysical properties of a sneeze or cough ejecta reported in the open literature are reviewed to characterize the two-phase flow (exhaled air and mucosalivary droplets). Sneeze or cough ejecta are studied as a two-phase buoyant puff at droplet sizes of 0.15-100 µm. Then droplet dispersion by a sneeze or cough ejecta to quasi-static environments is studied, from a physics view, to exploring the possibility of airborne transmission of viruses as SARS-CoV-2. Nozzle stokes numbers are analyzed at three Reynolds numbers, which correspond to the representative velocities of exhaled air (10, 15, and 20 m/s). Calculations show particles smaller than 5 µm are the critical case for airborne transmission, whereas particles less than 19 µm are affected by turbulent motions and remain airborne for long periods.*

***Key Words*: sneeze or cough ejecta, two-phase puff, droplet dispersion, nozzle Stokes number, airborne.**

1. INTRODUCTION

In the open literature, there is much information on the physical characteristics of human respiratory droplets, which are focused on talking, coughing, and sneezing. The experimental data coincide with many droplets generated in the sneeze ejecta, and there are similar droplets distributions on talking, coughing, and sneezing. Some authors, as Zayas et al. [1], found that there is no significant correlation between droplet size and cough frequency, age, and gender. However, there are controversies in the droplet sizes, exhaled air velocity, and droplet velocity by the measurement methods. The physical characteristics of air and droplets exhaled by sneeze, cough, or talking are relevant in the droplet dispersion. Droplet dispersion on controlled conditions allows understanding airborne transmission of viruses as SARS-CoV-2, which has caused 1.8 million deaths around the world [2] until January 2021. Therefore, the main objective of the review is to study physical characteristics of sneeze or cough ejecta and droplet dispersion in indoor environments. The review is focused on the physical mechanisms of droplet dispersion of two-phase buoyant puff. The sneeze or cough ejecta and the nozzle Stokes number in droplets of 0.15-50 µm are studied to understand the physical mechanisms of a potential airborne transmission of viruses as SARS-CoV-2 from a physics view.

2. PHYSICAL CHARACTERISTICS

There are many methods on droplet size and velocities of droplet or exhaled air by zneeze, cough or breathing. According to Zhang et al. [3], the Impaction Methods (IM) may cause particles to spread, splash, or finger and distort the correct particle size if identified by microscopy. Then other methods used are the Aerodynamic Particle Sizer (APS), Cough Aerosol Sampling System (CASS), High-Speed (HS) camera/video, Hot-Wire Anemometry (HWA) Interferometric Mie Imaging (IMI), Laser (Particle Size Analyser (PSA), Light Scattering (LS), and Diffraction System (DS)), Optical Particle Counter (OPC), Optical Particle Spectrometer (OPS), Particle Image Velocimetry (PIV), Scanning Mobility Particle Sizer (SMPS), Schlieren PIV (S-PIV), Shadowgraph Imaging (S-Imag), and Spirometer. The measurement methods, droplet size (D_p), and air/droplet velocity (u) on talking, coughing, and sneezing, are summarized in Table 1. Most experimental data show droplet sizes between 0.15-100 µm, average velocities of exhaled air of 4.5-21.25 m/s, and average velocities of droplets between 5-22 m/s.

Other characteristics of the sneeze or cough ejecta are the mouth opening area, which is based on human cough captured on photographs, and geometric plane shapes are approached as a semi-circular section (Gupta et al. [4]; Busco et al. [5]) or a rectangular sheet-like (Dbouk & Drikakis [6]). The semi-circular section approximation is considered as a characteristic length (equivalent diameter of an exit nozzle). This equivalent diameter is calculated from Gupta et al. [4] data (mouth opening area of 3.37-4 cm^2), which agrees to 3.4 cm^2 reported by Bourouiba et al. [7]. Calculation of the equivalent diameter is 0.021-0.023 m, which agrees with the mouth diameter (D_{em}) of 0.02 m used in many numerical simulations.

Table -1: Droplet size and velocity of airflow/droplet.

Author	Method	Dp (µm)	u (m/s)
[8]	APS	0.62-15.9 and 0.58-5.42^{dn}	na
[9]	APS	0.5-20	na
[10]	CASS	< 3 (70%)	na
[11]	HS camera	7-100	na

[12]	HS video	na	> 6^{droplet}
[13]	HS camera	160-1000	$14^{\text{droplet, maxv}}$
[14]	HS camera	na	$12\text{-}15^{\text{droplet, maxv}}$, $5^{\text{droplet, ps}}$
[15]	IM (solid)	$1\text{-}200^{\text{av}}$	na
[16]	IM (liquid)	50-860	na
[17]	IM (solid)	< 1	na
[18]	IM (solid)	55^{av}	na
[19]	IM (solid)	< 1	na
[20]	IM (solid)	$50\text{-}100^{\text{av}}$ and 5^{minv}	na
[21]	Laser PSA	$360^{\text{av, ud}}$ and $74.4^{\text{av, bd}}$	na
[22]	Laser LS	20-500	na
[23]	OPC	0.15-0.5 and $0.15\text{-}0.199^{\text{ps}}$	na
[24]	OPC	0.3-5	na
[25]	OPC	0.3-.499 (82%)	na
[26]	PIV	na	$6\text{-}22^{\text{droplet}}$, $11.2^{\text{droplet, av}}$
[27]	PIV	na	$10.6^{\text{air, female}}$, $15.3^{\text{air, male}}$
[28]	PIV-IMI	13.5^{av}	11.7^{air}
[29]	PIV	na	$1.15\text{-}28.8^{\text{air}}$, 10.2^{av}
[30]	PIV-HWA	na	$3.05^{\text{air, jet centre}}$ ($1.17^{\text{av, peak}}$)
[31]	SMPS-OPS	< 5 (99%)	$15.03\text{-}19.55^{\text{air, **}}$
[32]	S-PIV	na	$8^{\text{air, maximum av}}$
[33]	S-Imag	na	$4.5^{\text{air, maxv}}$
[4]	Spirometer	na	$4.75\text{-}21.25^{\text{air, *}}$

* value calculated considering the information provided in the paper.

** value calculated considering a mouth opening area of 3.37-4 cm²

av average value

bd bimodal distribution

dn droplet nuclei

minv minimum value

maxv maximum value

ps predominant size

ud unimodal distribution

The time of sneeze or cough expulsion phase lasted approximately 200-300 ms (Bahl et al. [14]; Bourouiba et al. [7]; Scharfman et al. [13]), although Busco et al. [5] and Zayas et al. [1] have reported average times of 500 ms and 700 ms, respectively. The average cone spreading angles are 24 ± 3° (Dudalski [30]), 25° (Gupta et al. [4], calculated by subtracting the directional angles), and 23.9° ± 3.48° (Tang et al. [32]). These angles agree to the universal spreading angle of 23.8° of the jet dispersion theory (Cushman-Roisin [34]). The potential core (Fig. 1) has not been presented in experiments, although a slight representation is shown in the velocity contour of a cough onset by Tang et al. [32]. Exhaled air temperatures on a sneeze or cough ejecta of 30-33°C are reported by Tang et al. [33]. These values agree to exhaled breath temperatures (33.8°C, 33.2°C±1.3°C, and 31.4-35.4°C) by Roberge et al. [35], Bijnens et al. [36], and Mansour et al. [37], respectively. Experimental measurements of exhaled breath RH showed variations of 65.0-88.6% and 41.9-91.0%, according to Mansour et al. [37]. However, Niesters et al. [38] and the ScienceBits website [39] reported values close to saturation and 95%, respectively.

3. PHYSICS OF DROPLETS DISPERSION

Fluids expelled on a sneeze or cough ejecta are mainly composed of exhaled air and mucosalivary droplets of various sizes. Sneezing or coughing is considered as a two-phase buoyant puff, which could study in two-time stages: stage 1) during the expulsion of fluids (air and droplets) and stage 2) post-expulsion of fluids. In stage-1 (fluids expelled), the fluid momentum is the dominant mechanism on the jet dispersion, and the physical phenomenon is approached as a one-phase turbulent jet dispersion. Froude number ($Fr=u_j/[(|\rho_j\text{-}\rho_a|/\rho_a)gD_{em}]$) and Richardson number ($Ri=|\rho_j\text{-}\rho_a|gD_{em}/\rho_j u_j^2$) are calculated for the two-phase jet, as shown in Table 2. The subscripts *j* and *a* are the jet (exhaled air) and the atmospheric air, respectively. Computations consider properties of exhaled air at 90% RH, which are calculated with data provided by Tsilingiris [40]. Results show Fr >> 1 and Ri << 0.1, which match criteria to determine if a jet dispersion is dominated by the initial momentum (Bricard & Friedel [41]). Later a turbulent cloud is formed (stage 2), and the jet trajectory of the centerline is curved by density difference as reported by Bourouiba et al. [7] and Wei & Li [42], and it's shown in nature video [43]. The buoyant dominates the physical phenomenon by velocity decay and warmer temperature. Then turbulent cloud moves along the cone in a meandering motion (see Fig. 1), which is approximated as a puff in a stratified environment. The turbulent cloud loses buoyancy and will move until the bulk cloud velocity is zero. A wide range of eddy sizes into de cloud disperse droplets and contribute to the cloud expansion, as seen in the nature video [43]. The average turbulence intensity reported by Dudalski [30] of a sneeze or cough is 8.9±3.9% at 45 times the equivalent diameter (D_{em} = 0.0217 m).

The physiochemical phenomena of the ejection of mucosalivary fluid are complex by the multiphase nature of the flow and the inhomogeneous liquid phase formed by droplets of different sizes, ligaments, bags of mucosaliva, and pearls (Scharfman et al. [13]). The human saliva presents a marked non-Newtonian flow effect (Haward et al. [44]), and there are salt/electrolytes (Johnson & Morawska [9]; Liu et al. [45]). In the sneeze or cough ejecta, droplets larger than 100 µm follow a projectile motion. Particles fall out by gravity as a rainout phenomenon with no appreciable vaporization (Wells [46]; Wei & Li [42]; Li et al. [47]; Yan et al. [48]), while droplet sizes less than 100 µm remain airborne (Duguid [15]; Li et al. [47]). Discussion of the phenomenon is conducted to droplets smaller than 100 µm because they are affected by flow dynamics of buoyant puff, and the evaporation rate is relevant. On small droplets (D_p < 100 µm), the evaporation is complex by the salt/electrolytes content in the saliva, the relative humidity of the exhaled air, and the droplet size. The salt/electrolytes content affects the droplet evaporation (Johnson & Morawska [9]; Zhang [49]), and the drying time increases around 20% (Liu et al. [45]), despite the physical properties of saliva are close to the water with 99.5% water, 0.3% proteins, and 0.2% inorganic/trace substances (Schipper et al. [50]). The relative humidity of the exhaled air has a strong effect on the drying time and increases almost 7-fold as humidity increase up to 90% (Li et al. [47]; Bhardwaj & Agrawal [51]). Then energy and mass transport are poor because liquid-phase and gas-phase could be considered in quasi-equilibrium. According to Wei & Li [42], RH is a key parameter to the droplet evaporation and spread of the virus. Finally, droplet evaporation increases as droplet size decrease by the enlarged specific surface area for heat and mass transfer. However, the evaporation rate of the microdroplet (D_p ≤ 2 µm) is slowed down because the droplet size is comparable to the mean free path of air molecules, according to Hołyst et al. [52].

A physics view of a sneeze or cough ejecta on the environment could help to understand the possibility of airborne transmission of viruses. Then a parameter that provides information on particle dispersion by its inertial response time is the Stokes number (*Stk*). According to Lau & Nathan [53], this parameter has a strong impact on the particle concentration and the subsequent evolution of the two-phase jet. There are four types of Stokes numbers (nozzle *Stk*, turbulent *Stk*, Kolmogorov *Stk*, and acceleration *Stk*), as described by Kennedy & Moody [54]. The nozzle Stokes number (Stk_n) has an overall representation of the phenomenon because it is based on the Stokes law and the convective time scale of the mean flow. So, the nozzle Stokes number ($Stk_n = C_c \rho_p D_p 2 u_j/18 \mu D_{em}$) is calculated with the equivalent diameter of the mouth opening (D_{em}) as a nozzle diameter. The subscript p is the particle (droplet), and C_c is the Cunningham coefficient caused by slippage. Droplet diameters are normalized (D_p/D_o) to a droplet size (D_o) of 5 µm, which remain suspended in the air, according to WHO [55]. Computations are conducted at droplet diameters up to 50 µm, where particles remain airborne. Three Reynolds numbers of exhaled air (Re_{ea}) are considered, according to experimental velocities (10, 15, and 20 m/s) presented in §2, at an average temperature of 33°C (see §2). The thermodynamic conditions considered for mucosalivary ejecta are presented in the notes of Table 2, and results are shown in Fig. 2.

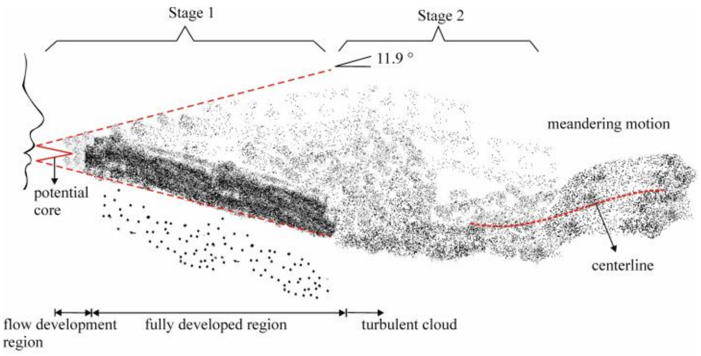

Fig -1: Physical representation of a sneeze or cough ejecta on quasi-static environments.

Table -2: Dimensionless parameters of the two-phase jet at two exhaled air temperatures.

Re_{ea}	T_{ea} (°C)		*Fr*		*Ri*1E5*	
13877	30	35	130.2	104.3	6.1	9.6
20815	30	35	195.3	156.5	2.7	4.3
27754	30	35	260.4	208.6	1.5	2.4

environmental air at 25°C and 101 kPa

D_{em} = 0.022 m

g = 9.8 m/s2

exhaled air properties at 90% of RH and 101 kPa

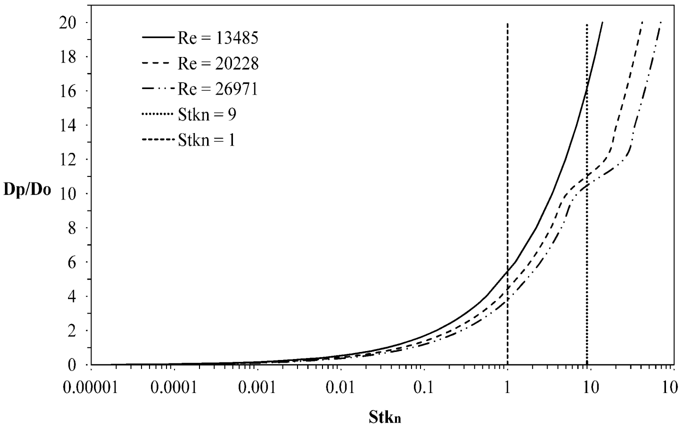

Fig -2: Nozzle Stokes number of a sneeze or cough ejecta.

Fig. 2 shows droplets smaller than 5 µm ($D_p/D_o = 1$) are in a mechanical quasi-equilibrium with the flow and are transported by the airflow as a gas-phase ($Stk_n << 1$). This result agrees with experiments conducted by van Doremalen et al. [56], who find SARS-CoV-2 remains viable in particles smaller than 5 µm for approximately 3 hrs with a half-life of 1.1-1.2 h. In the case of $Stk_n < 1$, the mechanical quasi-equilibrium is valid because particle dispersion is high, and slip velocity between particles and gas phase is low (Sun et al. [57]). Then droplets smaller than 19 µm ($D_p/D_o < 3.8$) are transported by airflow, and they remain airborne for long periods. Particles smaller than 50 µm ($D_p/D_o = 10$) respond to turbulent motions and are carried by the stream (Stk_n between 1-9). The influence of airflow on droplets between 50-100 µm is weak ($10 < Stk_n < 100$), although particles are still carried by airflow. Droplets larger than 100 µm ($D_p/D_o \geq 20$) are not affected by airflow because the nozzle Stokes number is higher than 100 ($Stk_n >> 1$). These results show particles smaller than 19 µm remain airborne in the environment for long periods, and the limit value is 50 µm. The particle dispersion is focused on a quasi-static environment under controlled conditions as confined spaces. Therefore, the airborne transmission of viruses in a quasi-static environment is possible from a physics view. The risk of infections in non-ventilated rooms is high, even if the distance is too large for direct transmission of the virus (Riediker & Tsai [58]).

4. CONCLUSION

Fluids expelled on a sneeze or cough could be studied in two-time stages, as a two-phase buoyant puff. In stage-1 (during the expulsion of fluids), the fluid momentum is the dominant mechanism on the jet dispersion. In stage-2 (post-expulsion of fluids), the buoyancy effect dominates the physical phenomenon. Nozzle Stokes numbers show particle sizes less than 5 µm remain airborne as a gas-phase ($Stk_n << 1$), which is the critical case to airborne transmission of viruses. Particles smaller than 19 µm ($Stk_n < 1$) are transported by airflow and remain airborne in the environment for long periods. Droplets between 50-100 µm are still carried by airflow, but airflow influence is weak ($10 < Stk_n < 100$), whereas droplets larger than 100 µm ($D_p/D_o \geq 20$) are not affected by airflow.

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