COVID-19 in air suspensions

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We analyze the stability of virus-carrying particles in air at equilibrium after the dissipation of the initial turbulent process produced by sneezing, coughing, breathing or speaking. Because the viruses are expelled mainly attached to small liquid droplets, with diverse sizes and weights, and the external environmental conditions can also be diverse, the subsequent motion spanes different spatial and temporal scales. We analize the validity of two simple models in this context. For droplet sizes larger than $100\,\mu m$, computing the time of decay to the ground and the distance travelled within a simple free fall model with empirical data extracted from the literature, we obtain distances in the range between 1 to 3 meters from the emitter, with a falling time of less than $1\,s$, similar to known recommendations for safe social distancing. For droplet sizes less than $100\,\mu m$ a model of motion in a viscous medium predicts that isolated viruses could remain suspended in quiet air for more than a month, while small droplets of $1\,\mu m$ in size can remain suspended for several hours, in qualitative agreement with experimental results on virus stability in aerosols.

Introduction

With the advance of the Covid-19 virus pandemic a discussion began regarding the proper use of masks as a safeguard against contagion. The initial advise from the World Health Organization was that only confirmed infected people should wear masks, in order to prevent transmission of the virus by sneezing and coughing [1]. But the high rate of propagation of the virus in different environments around the world raised a concern about this initial prescription. In particular, the fact that most of infected people go without developing symptoms make them potential transmitters of the desease. Together with restrictions on human circulation and social distancing, other important protective measure can be the generalized use of masks in public places, like hospitals, supermarkets and aircrafts [2]. Although it is believed that the main mechanism of transmission of the virus is through transport from infected surfaces to the mouth, nose or eyes, much less is known about transmission through the air. For how long the virus can remain suspended in the air ? What are dangerous concentrations ? How an initial concentration is propagated in space and time ? These are very broad questions, but relevant in order to build a robust response against contagion of air transmitted deseases, like Covid-19.

The mechanisms of propagation of virus in the air are diverse, depending on the nature of the process that expels the virus from inside an infected individual. When caughing or sneezing, a person ejects a turbulent cloud composed of liquid droplets in a wide range of sizes [3, 4]. Larger droplets fall down quickly and the cloud looses much of its initial momentum, until a buoyant gas of small droplets of sizes less than $100\,\mu m$ continuous expanding and spreading through space. Furthermore, in realistic situations, the effects of air currents due to openings in the builiding or air-conditioning must be taken into account. Results of simulations of realistic air flows carrying droplets after repeated coughing by a person in a room show that they can be transported for several meters before they settle on a surface or fall to the ground, thus having the potential to infect other people around in times of the order of seconds [5]. It was found that droplets of sizes less than $\sim 30\,\mu m$ can remain suspended in the air of the room after exiting the main current. Another way of exhaling the viruses in the air is when speaking and breathing. These are softer processes as compared with a cough or a sneeze, but they are equally potential ways of spreading the virus in the surroundings of an infected person. From these observations, it is clear that the answers to the above posed questions are not unique. Many factors influence the spatial

and temporal extensions of the virus in the air.

Our aim is to present a pedagogical discussion of the motion of the virus in suspended air, either considering a suspension of isolated viruses or a suspension of small liquid droplets with a viral load. When breathing, sneezing, talking or coughing, droplets with a viral charge are expelled from the mouth of an infected person. The droplets dispersed in the sorrounding air do not interact between them. Small droplets of sizes less than $10\,\mu m$ are abundant, forming aerosols which can be suspended in the air for a given amount of time. The main characteristics of the particles which determine the time of suspension in the air are their mass and size. In general, there is a distribution of particle masses and sizes in an aerosol. As a consequence of gravity, heavier particles will fall down at a faster rate than lighter ones. Nevertheless, recent reports show that the Covid-19 can remain suspended and active in aerosols for hours [6], making them potentially dangerous for the transmission of the desease to healthy people breathing around.

We will present some results based on simple physical models for the propagation of the particles with a viral charge once they come out from the mouth of an infected person. First, we will consider a virus that is ejected from the mouth as a free falling object under the only influence of gravity. We will analise the validity of this approximation with the size and weight of the particle. When valid, the results for this model predict that the virus should settle down on the ground after travelling approximately 1 to 3 meters, as suggested by different sources and transmitted in the general media [7]. Then, we will present some estimates of the air interparticle distance as compared with the size of the Covid-19 virus and of larger droplets. This will suggest us that the virus falls down in a viscous medium, the air. We will address the problem of the identification of the correct form of the drag force on the droplets, which has been considered many times in related contexts, see e.g. references [8, 9] for excellent discussions (see also [10, 11] for elegant analytical solutions to the equations of motion). Because expelled droplets, where the virus can be found, show a distribution of sizes and masses, we will present simple estimations of the rate and time of decay for typical sizes of the particles. We will not consider the initial turbulent flow nor external currents produced by air conditioning, for example [3, 5]. Instead, we will focus on the late regime of deposition of the small droplets that remain suspended in quiet air in equilibrium. The results can be considered as bringing lower bounds, or conservative estimations, to the spatial and temporal extensions of airborne virus. The analysis leads

us to conclude that typical droplets containing virus may remain suspended in quiet air for more than an hour, in agreement with experimental results reported recently [6].

A droplet in free fall

Free fall is the simplest model for the falling of a particle under the influence of gravity. It is assumed that there are no collisions with other particles during the trajectory. The position and velocities of the particles are given by Newton's equations of motion for a free fall [12]:

$$x(t) = x_0 + v_{0x}t \tag{1}$$
$$v_x(t) = v_{0x}$$
$$y(t) = y_0 + v_{0y}t + \frac{1}{2}g\,t^2$$
$$v_y(t) = v_{0y} + gt,$$

where x and y refer to horizontal and vertical directions respectively, (x_0, y_0) are the initial horizontal and vertical position coordinates of the particle, (v_{0x}, v_{0y}) are the corresponding components of the initial velocity vector, and $g = -9,8\,m/s^2$ is the acceleration of gravity (the minus sign reflects that distances grow positive from bottom to top, and gravity points downwards in this reference frame). Here, we will be interested in knowing how far a particle can travel, once it leaves the mouth of a person with an initial velocity vector in the horizontal direction, given by $(v_{0x}, v_{0y} = 0)$. The initial position of the particle will be set to $(x_0 = 0, y_0 = h)$, where h is the height at which the mouth is located. Within these conditions, from the third equation from (1) we can obtain the time to reach the floor $(y = 0)$ from an initial height $y_0 = h$:

$$t(h) = \sqrt{\frac{2h}{g}}. \tag{2}$$

Then, for example, a particle in free fall from a typical height of a person , $h = 1.7\,m$, will reach the floor in $t(1.7\,m) = 0.59\,s$. The horizontal distance it can travel is then obtained from the first of equations (1). It depends on the initial horizontal velocity v_{0x}. We chose two representative cases, extracted from an experimental study reported in [13]. We considered the maximal reported velocities, a conservative choice. The maximal initial velocity of a particle when talking or breathing was reported to be $v_1 \approx 1.5\,m/s$, while the maximal

$h[m]$	$t_h[s]$	$x_{v_1}(t_h)[m]$	$x_{v_2}(t_h)[m]$
1.5	0.55	0.83	2.77
1.6	0.57	0.86	2.86
1.7	0.59	0.88	2.95
1.8	0.61	0.91	3.03

TABLE I. Times of decay to the floor and horizontal distances of a spittle droplet when talking or breathing (x_{v_1}) and after sneezing or coughing (v_{v_2}), for four initial heights computed with a free fall model.

initial velocity when sneezing or caughing was found to be $v_2 \approx 5.0\,m/s$. Although in the cited report these corresponded to maximal speed, i.e. the scalar value of the velocity vector, we will consider them to be maximal representative of horizontal velocities, which we assumed in this case. Some typical values of time of decay and travel distance to the floor are shown in Table I.

As we can see in Table I, the times for a particle in free fall to settle on the ground from the typical height of a person is less than a second. The estimates of the horizontal distance travelled by the virus is less than $1\,m$ when talking or breathing, and around $3\,m$ from sneezing or coughing. These estimates roughly agree with others suggesting that keeping a distance of around $2\,m$ between people could be enough to represent a secure situation [7]. Nevertheless, as will be shown in the next section, the free fall approximation is not accurate for the decay of small droplets, which may stay suspended in the air for more than an hour [6, 14]. In the next section we will analyze the range of validity of the free fall model and show that for particles of sizes less than $100\,\mu m$ it is necessary to consider friction effects due to the viscosity of air.

Particle flow in a viscous medium

The density of dry air at $T = 20^o C$ and $1\,atm$ is $\rho_{air} = 1.2041\,kg/m^3$ [15]. Considering the air in a cube of volume $V = l^3$, we can estimate the typical interparticle distance in air to be:

$$l \approx (m/\rho_{air})^{1/3}, \tag{3}$$

where m is the average mass of an air particle (mainly nitrogen and oxigen molecules). The average molecular mass of dry air is $M_{air} = 28.97\,g/mol$ [16]. Considering that there are $N_A = 6.022 \times 10^{23}$ particles in a mol of substance, where N_A is Avogadro's constant, then $m = M_{air}/N_A \approx 4,81 \times 10^{-26} kg$. Thus, the typical interparticle distance in air is $l \approx 3,42 \times 10^{-9}\,m = 3.42\,nm$ [17]. To compare with, the approximate size of the Covid-19 virus is $d_C \approx 100\,nm$ [18]. Then, the virus will hit many particles in its trajectory through the air [19]. As a better model to compute characteristics of the trajectory of the virus we can assume that it is an approximately spherical particle falling in a viscous medium, the air. Furthermore, in the vast majority of cases, the virus will come attached to small liquid droplets expelled when talking or coughing, which have a larger volume than a single virus. Then, besides the effective downward gravitational force (the difference between the weight and buoyancy), one has to consider the upward drag force F_d on the particle. The nature and precise form of the drag force is a complex issue in fluid dynamics. A well known quantity to characterize the dynamical regime is the Reynolds number [20, 21]:

$$Re = \frac{\rho_f\,d\,v}{\eta}, \tag{4}$$

where ρ_f is the fluid density, d is the typical lengthscale of the object (the diameter in the case of a sphere), v the relative velocity, and η is the dynamic viscosity. For the microscopic objects of relevance for the present problem, the Reynolds number is very small. This claim will be justified a posteriori, once we compute the typical velocities involved. At small Reynolds number $Re < 1$, the drag force on a sphere of radius r is given by Stokes' law [3, 9]:

$$F_d = 6\pi\,\eta\,r\,v. \tag{5}$$

For sphere diameters less than $1\,\mu m$ a correction factor has to be considered [22]. As for the sizes of interest in our analysis this factor is of order one, we will use the approximate expression given above. In the vertical direction, this upward viscous force grows with time proportional to the velocity. It is opposed by the excess force between the weight and the buoyancy:

$$F_g = (\rho_s - \rho_f)\,g\frac{4}{3}\pi r^3, \tag{6}$$

where ρ_s is the density of the sphere. In this case, we will consider spherical droplets with $\rho_s = 997\,kg/m^3$ (the density of water) and $\rho_f = \rho_{air}$ given above. As $\rho_s \approx 1000\,\rho_{air}$, we can discard the density of air in F_g, which reduces to the weight of the spherical droplet,

$F_g \approx m_s g$. When the upward drag force F_d equals the weight of the particle, $F_d = F_g$, the droplet reaches mechanical equilibrium and, from then on, continues to fall with a constant terminal velocity given by:

$$v_T = \mu\, m_s g, \tag{7}$$

where $\mu = 1/6\pi\eta\, r$ is the droplet mobility in the fluid. For air, the dynamical viscosity is $\eta = 18.5\,\mu Pa \cdot s = 1.85 \times 10^{-5}\, kg \cdot m^{-1} \cdot s^{-1}$. Assuming that particles have an initial vertical velocity equal to zero, the terminal velocity is the maximal velocity it attains while falling down [23].

First of all, let's make an estimation of the limits of validity of the "free fall" model of the previous section. The free fall model assumes that gravity, i.e. the weight, is the only relevant force governing the motion of a particle. Then, as long as the weight is much larger than the drag force, the motion can be considered a free fall. Now, the weight of a spherical particle $F_g = m_s g$ can be written equivalently as $F_g = \rho_s V\, g = \rho_s\, (4/3\,\pi r^3) g$. It grows proportional to the volume, i.e. as the cube of its radius. On the other hand, the drag force produced by the viscosity of air grows linearly with the radius of the sphere, $F_d = 6\pi\,\eta\, r\, v$, much slower than the weight. Then, one can naively expect that the weight will quickly be much larger than the drag force as the size of the particle grows. Nevertheless, F_d also depends on the velocity, which is growing in the initial part of the motion, before it attains its terminal value. In any case, if the object falls down from rest, the real velocity when the particle has fallen down a height h will always be smaller than the corresponding free fall velocity v_{ff}, given by the last of equations (1) with the time given by (2), i.e.

$$v_{ff}(h) = \sqrt{2gh}. \tag{8}$$

We can set this value as an upper bound for the velocity of the particle after falling from a height h from rest. For example, in the present situation considering a typical height $h = 1.7\,m$, the free fall velocity is $v_{ff} = 5.77\,m/s$. Equating the weight with the drag force computed at v_{ff} we can obtain an upper bound for the radius of the particle r_c:

$$r_c = \sqrt{\frac{9}{2}\frac{\eta}{\rho_s g} v_{ff}}. \tag{9}$$

When the radius $r \geq r_c$ the drag force becomes irrelevant and the free fall model is valid. For the case under consideration $r_c \approx 200\,\mu m$. Several studies reported a wide range of droplet sizes, from the order of $1\,\mu m$ up to millimeters (see. e.g. Table 1 in [24]). Droplet

sizes are strongly dependent on the nature of the phenomenon, while talking, breathing, sneezing or caughing. For example, it has been found that sneezing produces larger droplets than coughing, and also that the velocity at which the droplets are expelled is considerably larger during sneezing. Other characteristics that may influence the final results reported in the literature are measurement techniques, the number of sampled indiviuals and their health conditions, among others. Last but not least, it is also known that droplets suffer evaporation after coming out of the respiratory tract. Then, the methodology of measurment is also important. The further from the mouth, the smaller will be the droplet size, due to evaporation. For droplets of size $\sim 200\,\mu m$ the time of evaporation is approximately $\approx 6.6\,s$ [25], i.e. larger than the time to reach the ground of all cases considered in Table I. Then, the free fall estimates are relevant for the motion of sneezing droplets of this size.

Now, let's consider some cases with droplets smaller than $10\,\mu m$, which represent the majority of cases found in experiments. To begin with, the smallest droplet of interest is a single Covid-19 virus. The size of the virus (its approximate diameter) is $d_C \approx 100\,nm = 0.1\,\mu m$, and its mass $m_C \approx 10^{-18}\,kg$ [14]. Then, its mobility and terminal velocity in dry air will be:

$$\mu = \frac{1}{6\pi\eta r} \approx 0.57 \times 10^{11}\,s \cdot kg^{-1}$$
$$v_T = \mu\,m_C g \approx 5,59 \times 10^{-7}\,m/s. \tag{10}$$

We note that the downward maximal velocity of a single virus is too small. Assuming that it began its fall with this vertical velocity at a height $h = 1.7\,m$, it will reach the ground in a time $t = h/v_T \approx 3 \times 10^6\,s \sim 35\,d$ (see Figure 1). Then, single viruses can remain suspended in undisturbed air for more than a month before settling down on the ground.

The previous case of single viruses floating freely in the air is probably not the most probable situation, nor the most dangerous from a contamination perspective, because the viral charge of the virus depends on its concentration. More relevant are droplets (mainly composed of water) with a virus charge in them. We will consider two typical cases: whole droplets as they come out from the mouth of an infected person, and droplets nuclei, that are the remanent of the original droplets once the water has evaporated. The typical size of droplet nuclei when coughing is around $d_{dn} \approx 1\,\mu m$ and that of whole droplets $d_d \approx 10\,\mu m$ [26]. Assuming that the droplets content is mainly water, the terminal velocities and
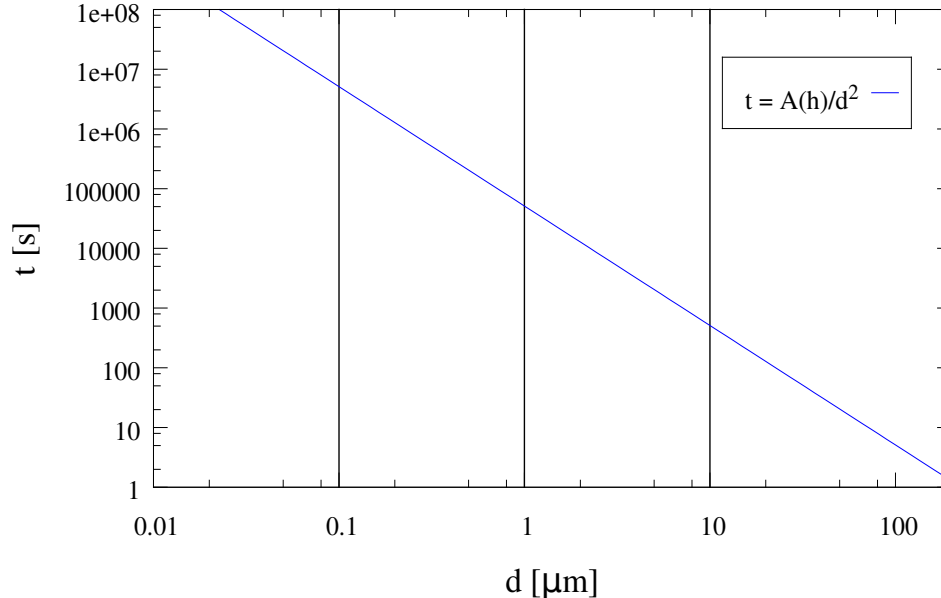
FIG. 1. Time to reach the floor versus size of droplets emitted while sneezing, coughing, speaking or breathing, assuming they fall in viscous air at low Reynolds number. Note the double logarithmic scale. $A(h)$ depends on the height from which the droplet is emitted (see text). Vertical solid lines correspond the examples computed in the text.

times of decay from a height $h = 1.7\,m$ for both cases are:

$$v_{dn} \approx 2.9 \times 10^{-5}\,m/s, \quad t_{dn} \approx 5.9 \times 10^4\,s \approx 16.3\,h \qquad \text{for droplets nuclei,}$$

$$v_d \approx 2.9 \times 10^{-3}\,m/s, \quad t_d \approx 5.9 \times 10^2\,s \approx 9.8\,mins \qquad \text{for water droplets.} \quad (11)$$

These order of magnitude estimates show that droplets nuclei of $\sim 1\,\mu m$ can remain suspended in air for around 16 hours, while droplets of $\sim 10\,\mu m$ can remain for around 10 minutes. These results are compatible with recent experimental determinations of the half-life of the Covid-19 virus in aerosols [6, 14]. In Figure 1 we can see that the sizes and falling times of relevant droplets emerging from expiratory events span many scales. From the considerations above, it is an exercise to show that the Stokes' model used here predicts that the falling time decays with the inverse square of the size:

$$t_h(d) = \frac{18\eta}{\rho\,g}\frac{h}{d^2}. \qquad (12)$$

For the typical height of a person, which is of interest in the present discussion, the effects of h on the final falling time is very small.

Finally, let us consider if the assumption of a drag force linear in the velocity is justified, i.e. if $Re \leq 1$ for the motions involved in the present problem. Recalling from equation (4) that the Reynolds number is proportional to the size of the object and its velocity, for the sizes of interest here let's consider a droplet with $d = 10\,\mu m$ for which $v_T = 2.9 \times 10^{-3}\,m/s$. In this case $Re \approx 1.9 \times 10^{-3}$. Then, the problem considered in this work is in the very small Reynolds number regime. Even for droplets an order of magnitude larger, $d \sim 100\,\mu m$, the terminal velocity will be of the order of $0.1\,m/s$, and $Re \sim 1$.

Diffusion in quiet air

After realizing that a small droplet can remain suspended in quiet air for several hours, one can ask how far it can travel before settling on the ground. Assuming that, after the initial cloud looses most of its initial momentum, the remaining gas undergoes diffusion in quiet air, we can estimate how far a micro droplet can travel during a given time. In a diffusive process particles undergo random displacements without a net direction, due to collisions with other particles. Then, although the average particle displacement is zero, a measure of how far it goes in its random walk in sapce is given by the root mean squared displacement:

$$r_{rms} \equiv \sqrt{\langle r^2(t) \rangle} = (6\,Dt)^{1/2}, \tag{13}$$

where $D = \mu k T$ is the diffusion constant [27], which depends on the mobility of the particle in the medium and on the temperature. For droplet nuclei of $1\,\mu m$ at $20^o C$, the diffusion constant is $D \approx 12.13 \times 10^{12}\,m^2/s$. Then, the order of magnitude of r_{rms} for a time span of the order of a few hours is $r_{rms} \sim 1\,mm$. We can conclude that, in the absence of currents, micro droplets of these sizes stay practically around the same region where the initial cloud lost its initial momentum. In a real situation, there will always be some degree of turbulence in the medium, due to the initial process of sneezing or coughing, or even because people walk around. Although one cannot expect that diffusion is the dominant mechanism of propagation of the final cloud of micro droplets, this is useful to illustrate the slow time scales of dissipation of the gas of droplets in the absence of currents. Small currents of air are responsible for propagating the remaining cloud of virus-carrying micro droplets away from the source, creating a potentially infectious atmosphere in closed spaces which can remain for quite a long time.

Conclusions

We have shown estimates of the motion of droplets in the air, depending on droplet size and initial velocities, as they leave the mouth during talking, breathing, sneezing or coughing. Depending on the size of the droplets, which can vary in a wide range, two different models can give useful estimates of the time of persistence of the droplets in quiet air. For droplets larger than $\approx 200\,\mu m$, typical of sneezing events, a free fall model is appropriate. They can attain distances of several meters, justifying recommendations for social distancing. On the other side, for droplets of sizes less than $\approx 200\,\mu m$, the free fall model is not accurate, and a model of motion in viscous air is necessary. Our results show that typical respiratory droplets with sizes $\leq 10\,\mu m$ can remain suspended in dry quiet air from several minutes to hours. The time of evaporation of water droplets of sizes as small as $10\,\mu m$ is much less than a second [25], leaving droplets nuclei. Then, we conclude that droplet nuclei, which can be suspended in dry air for hours, may be carriers of the virus in quiet air environments, like in a closed room or in an aircraft.

Together, these results suggest that airborne transmission of the virus may be a possible mechanism of infection. This also points that the use of masks, even for healthy people, may be a valid way of reducing contagion of Covid-19. More experimental studies are needed in order to confirm if airborne transmission is relevant as compared with other known mechanisms, like surface mediated ones.

Finally, it is important to stress that the results presented here, based on simplified models of motion, represent lower bounds for the time of stability of small droplets in the air. Considering realistic situations, taking into account small currents and/or convection mechanisms in closed spaces do not contradict the present conclusions [4, 5, 28]. Inclusion of these and other effects, like the process of evaporation of droplets, are interesting routes for future research.

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