The dispersion of spherical droplets in source–sink flows and their relevance to the COVID-19 pandemic

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Dynamics of spherical droplets in source-sink pair flow fields

C.P. Cummins,1,2,3 O.J. Ajayi,1 F.V. Mehendale,3 R. Gabl,4 and I.M. Viola4
1)Maxwell Institute for Mathematical Sciences, Department of Mathematics, Heriot-Watt University, Edinburgh, EH14 4AS, UK
2)Institute for Infrastructure & Environment, Heriot-Watt University, Edinburgh, EH14 4AS, UK
3)Centre for Global Health, Usher Institute, College of Medicine and Veterinary Medicine, University of Edinburgh, EH8 9AG
4)School of Engineering, University of University, Edinburgh, EH9 3FB, UK
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In this paper, we investigate the dynamics of spherical droplets in the presence of a source-sink pair flow field. The dynamics of the droplets is governed by the Maxey-Riley equation with Basset-Boussinesq history term neglected. We find that, in the absence of gravity, there are two distinct behaviours for the droplets: small droplets cannot go further than a specific distance, which we determine analytically, from the source before getting pulled into the sink. Larger droplets can travel further from the source before getting pulled into the sink by virtue of their larger inertia, and their maximum travelled distance is determined analytically.

We investigate the effects of gravity, and we find that there are three distinct droplet behaviours categorised by their relative sizes: small, intermediate-sized, and large. Counterintuitively, we find that the droplets with minimum horizontal range are neither small nor large, but of intermediate size. Furthermore, we show that in conditions of regular human respiration, these intermediate-sized droplets range from a few μm to a few hundred μm. The result that such droplets have a very short range could have important implications for the interpretation of existing data on droplet dispersion.

I. INTRODUCTION

The transport of inertial particles in fluid flows occurs in many problems arising in engineering and biology, such as the build-up of microplastics in the ocean1–3 and respiratory virus transmission through tract droplets.4 The Maxey-Riley equation5 describes the motion of a finite-sized spherical particle in an ambient fluid flow. The equation is a representation of Newton’s second law, in which the forces acting on the particle include a Stokesian drag force, an added mass force, a gravity force, the force due to the undisturbed flow, and a Basset-Boussinesq history term. The equation takes the form of a second-order, implicit integro-differential equation with a singular kernel, and with a forcing term that explodes at the starting time.6 The equation has been applied to model the dynamics of aerosol comprising particles of various density ratios7, feeding mechanism of jellyfish8,9, and the dynamics of inertial particles in vortical flows10,11.

The Basset-Boussinesq term accounts for the drag due to the production of vorticity as the particle is accelerated from rest. It is difficult to include this term numerically, and is often omitted on the assumption that particles move in a quasistatic manner.12 This assumption breaks down in bubbly and slurry flows, where the Basset-Boussinesq term accounts for a quarter of the forces on the particle when density ratio \( R = 2\rho'_f / (\rho'_p + 2\rho'_f) \) is greater than 2/3, where \( \rho'_f \) is the fluid density and \( \rho'_p \) is the particle density. Recent advances13 have shown that the full Maxey-Riley equation can be represented as a forced, time-dependent Robin boundary condition of the 1-D diffusion equation. Here, the authors found that a particle settling under gravity relaxes much more slowly \( (t^{-1/2}) \) to its terminal velocity than if the Basset-Boussinesq was neglected, where it relaxes exponentially quickly.14

In this paper, we examine the transport of inertial particles in source-sink flows.15 Such a flow could represent the trajectories of water droplets emitted from coughing, sneezing2–4, or breathing and in the presence of extraction, such as an air-conditioning unit or air current. Since the dynamics of settling droplets is significantly affected by their size, it is important to understand the impact that the emitted particle size has on the destination of such a particle in a source-sink flow. In particular, since droplets are vectors for infectious diseases such as COVID-19, it is imperative that we understand the particle dynamics in such flows to mitigate the spread of the disease.

The paper is organised as follows: in Section II, the mathematical model is presented and non-dimensionalised. The results are presented in Section III for small II A and intermediate-sized II B particles in the absence of gravity. Gravitational effects are considered for small particles in III C and for intermediate-sized particles in III D. In Section IV, we present applications for our results for human breathing without IV B and with IV C the inclusion of extraction. Finally, we discuss our findings in Section V.

II. MATHEMATICAL MODEL

Consider a source producing air of density \( \rho'_\text{air} \) and viscosity \( \nu'_\text{air} \) with volume flux of \( Q'_1 \), containing spherical liquid droplets of radius \( a' \) and density \( \rho'_\text{drop} \) which are emitted with a characteristic velocity \( U'_\text{source} \). Let us represent the 3D velocity field \( \mathbf{u}'_{\text{source}}(\mathbf{x}') \) at a position \( \mathbf{x}' \) of the emitted air as a point...
source of strength \( Q'_s \), centred at the origin:

\[
\mathbf{u}'_{\text{source}}(x') = \frac{Q'_s x'}{4\pi|x'|^3}.
\]  

(1)

We include an extraction unit as a point sink of strength \( Q'_e \) located at a position \( x_0 \) as follows:

\[
\mathbf{u}'_{\text{sink}}(x') = -\frac{Q'_e (x' - x_0)}{4\pi|x' - x_0|^3}.
\]  

(2)

The resulting airflow is given by the linear superposition of these two flows:

\[
\mathbf{u}'(x') = \frac{Q'_s x'}{4\pi|x'|^3} - \frac{Q'_e (x' - x_0)}{4\pi|x' - x_0|^3}.
\]  

(3)

The natural timescale of the problem emerges as \( T' = |x_0|/U' \). We non-dimensionalise \( (3) \) according to

\[
x = x'/|x_0|, \quad u = u'/U',
\]  

(4)

which gives the nondimensionalised expression for the airflow velocity.

\[
\mathbf{u}(x) = \Lambda \left( \frac{x}{|x|} - \gamma \frac{x - x_0}{|x - x_0|} \right),
\]  

(5)

with \( \Lambda = Q'_s / 4\pi U' |x_0|^2 \), \( \gamma = Q'_e / Q'_s \), and \( x_0 = x_0' / |x_0| \).

The velocity of the droplet embedded in this background airflow obeys the Maxey–Riley equation:

\[
\ddot{\mathbf{v}}(t) - \frac{3}{2} R \left. \frac{D \mathbf{u}}{Dt} \right|_{\mathbf{X}(t)} - \left( 1 - \frac{3}{2} R \right) \mathbf{g} - A (\mathbf{v}(t) - \mathbf{u}(\mathbf{X}(t), t)) = \frac{9}{2\pi} \frac{R}{St} \int_0^t \left( \frac{\dot{\mathbf{X}}(s) - \mathbf{u}(\mathbf{X}(s), s)}{\sqrt{t - s}} \mathbf{X}(s) - \mathbf{u}(\mathbf{X}(s), 0) \right) ds + \frac{\mathbf{v}(0) - \mathbf{u}(\mathbf{X}(0), 0)}{\sqrt{t}}.
\]  

(6)

where \( \mathbf{X}(t) \) is the position of the droplet at time \( t \), \( \mathbf{v}(t) = \dot{\mathbf{X}}(t) \) is its velocity, and

\[
R = \frac{2g'}{\rho' / u' + 2\rho_{\text{air}}} \quad \text{and} \quad A = \frac{R}{St},
\]  

\[
St = \frac{2}{9} \left( \frac{d'}{|x_0|} \right)^2 Re, \quad \mathbf{g} = \frac{|x_0| \mathbf{g'}}{U' |x_0|^2}.
\]  

(7)

with \( g' \) the acceleration due to gravity vector, \( Re = U'|x_0|/\nu' \) is the Reynolds number, and \( St \) is the particle Stokes number. Note here that the Faxén correction terms have not been omitted: they are identically zero since \( \Delta u = 0 \).

The approximate ratio of Basset history drag to Stokes drag is \( O(St^{1/2}) \), which, for the range of \( St \) we are interested in, is generally much less than one. In the remainder of the paper, we neglect the Basset history term since we anticipate its magnitude is negligible compared to the Stokes drag term for the parameters of interest to us, and the resulting equation is

\[
\ddot{\mathbf{v}}(t) - \frac{3}{2} R \left. \frac{D \mathbf{u}}{Dt} \right|_{\mathbf{X}(t)} = \left( 1 - \frac{3}{2} R \right) \mathbf{g} - A (\mathbf{v}(t) - \mathbf{u}(\mathbf{X}(t), t)).
\]  

(8)

A. Computational considerations

The resulting equations \( (8) \) are a set of three coupled second-order non-linear ordinary differential equations (ODEs) for the position vector \( \mathbf{X}(t) \). The algebra involved in computing the material derivative in \( (8) \) is straightforward, but cumbersome, and it is omitted here. This set of equations does not admit analytical solutions in general, so must be solved numerically.

We solved the equations by expressing them as a system of six first-order ODEs using Matlab’s ode15s, a variable-step, variable-order solver based on the numerical differentiation formulas. This was performed on a laptop equipped with an Intel(R) Core(TM) i9-9980HK CPU (2.40GHz) and 32GB of RAM; and each trajectory took on average 0.015 seconds to compute. In each of our plots, we use 31 trajectories, giving a total simulation time of approximately 0.47 seconds.

Computational fluid dynamics (CFD) is an alternative approach to the presented mathematical model. For most applications the basic Navier-Stokes (NS) equations are simplified to Reynolds-averaged Navier–Stokes (RANS) equations by time-averaged and consequently removing the fluctuating quantities. Consequently, the computational needs can be reduced significantly in comparison to a full solution of the NS but the effects of the turbulence (Reynolds stress) has to be modelled with a specific model. The complexity of the equations still requests a numerical approximation and hence a solution based on a time and space discretisation (time step and computational grid).

To show the advantage of the presented mathematical approach, a comparable study using the commercial CFD model ANSYS-CFX was conducted. For this simplified investigation, it was assumed that the particles follow the air based on an additional transport equation. Typical calculation times for one set of parameters were between 3 to 4 hours (Processor Intel(R) Xeon(R) CPU E3-1275 v3 @ 3.50GHz and 32GB of RAM), which depends on the size of the fluid domain, applied mesh, complexity of the geometry as well as the specific additional models. Nevertheless, this comparison of required time for one run shows the significant potential of the presented approach, which allows us to identify the most important combinations out of a wide variation of variables in a computational time that is at least four orders of magnitude faster than CFD.

III. THE RESULTS

A. Small droplets in the absence of gravity

In the absence of gravity, \( (8) \) reads (dropping the explicit time dependence)

\[
\ddot{\mathbf{v}} - \frac{3 R}{2} \left. \mathbf{u} \cdot \nabla \mathbf{u} \right|_{\mathbf{X}(t)} = -\frac{R}{St} \left( \mathbf{v} - \mathbf{u} \right|_{\mathbf{X}(t)}).
\]  

(9)

In \( (9) \), for small droplets \( (St \ll R) \) emitted from the source, the balance is between the first term on the left-hand side and...
the right-hand side, so that the velocity rapidly adjusts to the
background flow \( v \approx u_{X(t)} \).

We are interested in whether droplets move away from or
towards the sink. To this end, we look for trajectories for
which \( v > 0 \):
\[
v = \frac{dX}{dt} > 0 \iff \frac{X}{|X|^3} > \frac{\gamma(X - x_0)}{|X - x_0|^3}, \quad (10)
\]
If we take \( x_0 = [1, 0, 0] \), then the trajectory that emerges from
the source and travels in the direction of the negative \( x \)-axis
is the one that gets the greatest distance away from the sink.
Hence, let us consider this inequality in the first component,
and along the line \( y = 0, z = 0 \):
\[
\frac{dX(t)}{dt} > 0 \iff \frac{X}{|X|^3} > \frac{\gamma(X - 1)}{|X - 1|^3}. \quad (11)
\]
We are interested in where the flowfield changes direction,
since this indicates the maximum distance droplets emitted at
the source can travel before moving towards the sink. To this
end, let us choose a point \( x = -\lambda \) along \( y = 0 \) and \( z = 0 \); then
this inequality tells us that
\[
\frac{dX(t)}{dt} > 0 \iff \gamma > (1 + \frac{1}{\lambda})^2. \quad (12)
\]
This inequality can hold only if \( \gamma > 1 \). This makes sense, since
flow is directed towards the sink only if the sink is stronger
than the source.

Figure 1 shows the trajectories for small droplets \((St \ll R)\)
in the presence of a source-sink pair: the source is located
at the origin (green disk) and the sink is located at \( x = 1 \)
along the \( x \)-axis (red disk). For \( \gamma = 1 \) (Figure 1b), we have
equal strength and droplets can take large excursions from
the source before returning to the sink. As \( \gamma \) increases, the trajec-
tories emanating from the source occupy an increasingly
compacted region (Figure 1d). We can use this inequality
above to define a region
\[
|\lambda| < \frac{\sqrt{\gamma + 1}}{\gamma - 1}, \quad (13)
\]
such that small droplets do not get further than a distance
\( |\lambda| \) before travelling towards the sink. The circle with radius
\( |\lambda| \) is shown in Figure 1d (dashed curve). Observe that, as one
gets increasingly close to the source \((\lambda \rightarrow 0)\), the inequality tends
to
\[
\frac{dX(t)}{dt} > 0 \iff \gamma > \frac{1}{\lambda^2}, \quad (14)
\]
meaning that, in order to maintain trajectories moving away
from a given test point, the sink strength needs to increase
quadratically with distance of the test point to the source.

B. Intermediate-sized droplets in the absence of gravity

For \( St = O(R) \) and \( St \gg R \), the particle is slowed down ex-
ponentially according to
\[
v(t) \approx v(0) \exp[-(R/St)t], \quad (15)
\]
which represents a balance between inertia and drag forces.
Provided \( \gamma > 1 \), and in the absence of gravity, in the long-
term, the particle will always migrate towards the sink. How-
ever, in the case of intermediate-sized droplets, the maximum
distance travelled by the droplet before it moves towards the
sink is given by \(|v(0)|/\gamma R/St\). Since the initial velocity of
the droplet is chosen to be the same as the surrounding fluid, then
we can write the maximum distance as \(|v(X(0), 0)|/\gamma R/St\).
In our non-dimensionalisation, our characteristic velocity \( U' \)
was chosen to be that of the outlet. Hence, in this non-
dimensionalisation, \(|v(X(0), 0)| = 1 \). Since we also set our
initial condition on the velocity to be the same as the fluid’s
velocity at the source, then we have the following condition
on \( X(0) \):
\[
|X(0)| = \sqrt{\lambda}. \quad (16)
\]
Figure 2 shows the trajectories of intermediate-sized droplets
for \( \gamma = 3 \) in the absence of gravity. The striking feature of
the plot is the shift from a regime where the maximal extent of
the trajectories as predicted by (13) is no longer valid and must
be replaced with a circle of radius \( St/R \).

C. The effect of gravity on small droplets

As droplets move from the source to the sink, gravity at-
tempts to pull them vertically downwards. Over the timescale
of the problem: i.e., the average time it takes a droplet to travel
from source to sink, gravity may or may not have an apprecia-
table effect. Intuitively, one would imagine that smaller droplets
are influenced more by the airflow than gravity: for stronger
sinks, the effect of gravity is comparatively less. Also, intu-
atively, one would think that this holds true provided that the
source and sink are not too far away.

For \( St \ll R, R < 2/3 \), and in the absence of gravity, there are
three fixed points: the source, sink and a saddle point located
at \( x = -|\lambda| \) along the \( x \)-axis (Figure 1c). When gravitational
effects are included, the fixed point at \( x = -|\lambda| \) moves clock-
wise along about the origin as the effect of gravity is increased
(see Figure 2a). A fourth fixed point (saddle) is created far
from the source-sink pair, which gradually moves towards
the sink (Figure 3b, c) as the effect of gravity is increased. In
Figure 3d, the separatrices (indicated as blue dashed curves)
show that there is a wedge of trajectories that escape the pull
of the sink. As might be expected, these trajectories are those
that point directly away from the sink.

D. The effect of gravity on intermediate-sized droplets

Small droplets are deflected by gravity, but generally feel
the pull of the sink. Whether or not they are pulled in is de-
termined by the interaction of gravity, the angle of their trajec-
tory, and the strength of the sink. As the droplets become
larger, gravitational effects dominate, and the sink becomes
ineffective. In Figure 3, we show how the droplet trajectories
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FIG. 1. The trajectories $\mathbf{X}(t)$ in the $xy$ plane of small droplets $St \ll R$ with a background source-sink pair of various strengths $\gamma$. In these plots, $R = 0.001$, $\Lambda = 0.0001$, $|g| = 0$. The trajectories do not change for changing $R$. The dashed circle indicates the predicted maximal distance that a particle can travel in this regime, calculated using the inequality [13].

behave as $St$ is increased. Figure 4a, show the familiar situation where the droplets are so small that gravity does not appreciably affect their trajectory.

As gravity is increased, Figure 4b, shows that there are a range of trajectories with ejection angles $\alpha$ (defined with respect to the positive sense of the $x$-axis) around the source that are deflected downwards away from the sink. This is consistent with previous sections. However, at a critical $St$, each ejection angle is deflected downwards by gravity (Figure 4c). In this case, the maximum horizontal distance travelled by the droplets is very small. Interestingly, this trend is not monotonic. Further increasing $St$, the trajectories adopt a ballistic trajectory (Figure 4d). Such droplets can move in very close proximity to the sink, but are not pulled into it (Figure 4d).

IV. EXAMPLES OF APPLICATION

A. Background on Respiratory Virus Transmission

One of the possible applications of this paper, is to underpin more sophisticated analytical or numerical models to study the transmission of respiratory viruses. In medical applications, it is common practice to categorise the emitted fluid particles as larger droplets from 5 $\mu$m to 1 mm in diameter that have a ballistic trajectory, and aerosol that remains airborne. Droplets smaller than 5 $\mu$m and desiccated droplet nuclei are known as aerosol, which can remain airborne for several hours [14, 15]. Respiratory viruses are transmitted from virus-laden fluid particles to the recipient through (1) aerosol inhalation; or (2) droplet deposition on the recipient’s mouth, nose or conjunct-
Stokes number is not sufficiently large to have a ballistic trajectory. The relative importance of aerosol (1) and droplet (2 and 3) virus transmission is not always known, and it is yet to be established for the SARS-CoV-2 virus. Counterintuitively, it has been argued that aerosol could be more dangerous than larger droplets. Smaller droplets (≤ 5 μm) suspended in aerosol might carry a higher concentration of virus than larger droplets (>5 μm). The largest droplets are less likely to penetrate deeply in the respiratory system and might be deactivated by the effective first structural and defence barrier of the mucosa. Conversely, aerosolised virus half-life exceeds one hour and can be transported airborne through inhalation deep into the lungs, avoiding the defences of the upper respiratory system. Furthermore, aerosol inoculation has been shown to cause more severe symptoms than droplets administered by intranasal inoculation and the dose of influenza required for inoculation by the aerosol route is 2-3 orders of magnitude lower than the dose required by intranasal inoculation.

To apply our model to aerosol dispersion, we consider the particles ejected by a person talking. A person ejects about tens of fluid particles per second with diameters between 0.1 μm to 1 mm and with a speed of the order of 1 m s⁻¹. Because this is the most frequent source of aerosol, this accounts for most of the aerosol inhaled by other people. Coughing leads to the ejection of 100-1000 fluid particles per second with a speed around 10 m s⁻¹, while sneezing generates 1000-10,000 fluid particles per second with a speed of up to 20 m s⁻¹. The values presented in this paragraph should be taken as indicative because there is a significant variability between different experimental studies.

Some of the physics that is not considered in this work, is the particle-particle interaction and evaporation. In fact, fluid particles are ejected through a jet that transports particles in the range of 2 μm – 150 μm, i.e. the aerosol, while the largest droplets have a ballistic trajectory independent of the surrounding flow. The jet can be either laminar or turbulent when breathing and speaking, while coughing and sneezing always results in a turbulent jet with a diameter-based Reynolds number higher than 10⁴. Once ejected, the air jet extends along a straight trajectory; its diameter increases linearly with the travelled distance, while the mean velocity linearly decreases, and the turbulent statistics remain constant (i.e. the jet is self similar). Once the largest particles with a ballistic trajectory have left the air jet, the jet bends upwards due to the buoyancy force caused by the temperature and thus density difference. Smaller size particles (<100 μm) are transported by the jet while they evaporate. Once a droplet exits the jet, it falls at its settling speed. For a particle with a diameter of 50 μm and 10 μm, the settling speed is less than 0.06 m s⁻¹ and 0.03 m s⁻¹, respectively. The smallest of these two droplets is likely to land in the form of a desiccated
FIG. 3. The trajectories $X(t)$ in the $xy$ plane of small droplets $St \ll R$ with a background source-sink pair with strength ratio $\gamma = 5$ and for various strengths of gravity. In these plots, $R = 0.001$, $\Lambda = 0.0001$. The trajectories will be different for different choices of $R$. The dashed circle indicates the predicted maximal distance that a fluid parcel can travel when ejected from the source. The black crosses indicate the position of saddle fixed points.

nucleus. In fact, while a droplet with a diameter of 50 $\mu$m evaporates in about 6 s, a 10 $\mu$m droplet evaporates in less that 0.1 s. Once these droplets leave the jet, they can still be transported by ambient air currents, which have speeds typically in excess of 0.01 m s$^{-1}$. These currents are modelled by the sink-source flow field discussed in this paper.

A key issue that is discussed in this study is the extent to which the cloud of droplets and aerosol are displaced into the neighbouring environment, as this is associated with virus transmission risk. Previous studies estimated that the overall horizontal range of the droplets generated while breathing and coughing before they land on the ground is around 1-2 m [50,51]. These studies led to the CDC [52] and WHO [53] social distancing guidelines. Nonetheless, the complex physics involved, which includes knowledge of the particle size distribution, their speed of evaporation, the viral charge of droplets of different size, the diffusivity of the virus-laden particles, etc., makes it difficult to assess which is the effective dispersion of virus-laden fluid particles into the environment once ejected. It was found that the largest droplets generated by sneezing can reach a distance as high as 8 m [2,3,50], while aerosol dispersion is highly dependent on the temperature, humidity and air currents. For these reasons, this paper does not aim to provide definitive measures for the aerosol displacements but contributes to building a body of evidence around this complex question.
FIG. 4. The trajectories $X(t)$ in the $xy$ plane with a background source-sink pair with strength ratio $\gamma = 5$ and for various Stokes numbers $St$. In these plots, $R = 0.001$, $\Lambda = 0.0001$, and $|g| = 1$. The trajectories will be different for different choices of $R$. The dashed circle indicates the predicted maximal distance that a fluid parcel can travel when ejected from the source.

B. Predicted Droplet Dispersion

Currently, there is a large amount of disagreement in the reported spectra of droplet sizes in respiratory events. The analysis is complicated by various factors including the evaporation of the droplets as they travel from the source, which in turn, is influenced by ambient humidity and temperature. Recent mathematical modelling of droplet emission during talking have categorised droplets into one of three groups: small ($< 75 \mu m$), intermediate (75-400$ \mu m$) and large ($> 400 \mu m$). Small droplets approximately follow the air and can travel a great distance by weakly feeling the effects of gravity. Large droplets can also travel a large distance due to their inertia. However, the intermediate-sized particles feel strongly both gravity and drag, and their trajectory is a complex interaction of these effects. Similar trends were observed in computational fluid dynamics simulations of previous authors.

In this section, we examine the problem from a much simplified perspective: we ignore evaporation entirely. We model the situation as a point source emitting droplets of various sizes in the presence of gravitational forces, and compute the maximum horizontal distance travelled by these droplets. In this case, $Q' = 0 \ L \ min^{-1}$, and other quantities such as jet speed, direction and spread are taken from recent experimental studies of the authors and these quantities are summarised in Table I.

We find that for both heavy and quiet breathing, the maximum distance travelled by droplets depends strongly on the droplet diameter – see Figure 5. As expected, small droplets can travel many metres, however, we see that there is an
intermediate range of droplet diameters where the horizontal distance is minimised. For quiet breathing, this minimum occurs between 69 µm < d < 76 µm, while for heavy breathing this minimum occurs between 50 µm < d < 56 µm. This multi-modal behaviour is reminiscent of that in previous experimental studies that measured the size distributions of droplets in various respiratory events such as talking and coughing\(47,48\) and sneezing\(50\). The multi-modal behaviour observed in experiments is attributed to the different generation modes: bronchiolar, laryngeal and oral. In our simplified model, we do not have any assumption on the biological origin of the droplet: the existence of the minimum is a characteristic of the droplets themselves and cannot be used as an indicator of the underlying particle size distribution.

In order to unpick the physics, observe that the drag force scales as the diameter of the droplet, but the weight of the droplet scales as the diameter cubed, hence for large droplets, the drag force is negligible in comparison with the inertia of the droplet scales as the diameter, but the weight of the droplet is of the same magnitude as the gravitational force. Hence, we have the following designations:

(I) small droplets with \(St < \frac{2RA}{(1 - \frac{3}{2}R) |g|}\), which act like fluid tracers

(II) intermediate-sized droplets with \(\frac{2RA}{(1 - \frac{3}{2}R) |g|} < St < \frac{R}{(1 - \frac{3}{2}R) |g|}\)

(III) large droplets with \(St > \frac{R}{(1 - \frac{3}{2}R) |g|}\), which adopt ballistic trajectories.

This is illustrated in Figure 6, where the black curves are the numerical solutions to quiet (a) and heavy (b) breathing at zero direction and spread angle\(59\) and the red dashed curves indicate the expression in (18) for large \(St\) and (19) for small \(St\). The black vertical lines indicate the distinction between small and intermediate-sized (see (20)) and intermediate-sized and large droplets (see (21)).

Reverting to dimensional quantities, we have the following range of intermediate-sized droplets.

\[
\sqrt{\frac{9\nu_{air}'Q_1'}{\pi g'\left|X'_{ch}\right|^2(\rho_{air}' - \rho_{drop}')}} < d' < 2\sqrt{\frac{9\nu_{air}'Q_1'U'}{2g'(\rho_{drop} - \rho_{air}')}}.
\]

Plugging in the numbers from Table I, we have the approximate range:

\[3 \mu m < d' < 138 \mu m,\]
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Heavy breathing
Quiet breathing

FIG. 5. The maximum distance ($L'$) travelled for droplets of various diameters ($d'$) with quiet (light grey) and heavy (dark grey) breathing. The dashed curve corresponds to trajectories with with ejection angle equal to $\alpha + \beta/2$, while the solid curve corresponds to trajectories with ejection angle equal to $\alpha - \beta/2$ in Table I.

for quiet breathing and

$$7\mu m < d' < 414\mu m,$$  (24)

for heavy breathing. Our upper bound is in good agreement with previous categorisations of droplets, although our lower bound seems to be smaller than those found by previous authors.

C. The effectiveness of extraction on droplets

Consider a person breathing air of density $\rho_{\text{air}}' = 1.149\text{kgm}^{-3}$ and kinematic viscosity $\nu_{\text{air}}' = 16.36 \times 10^{-6}\text{m}^2\text{s}^{-1}$ containing water droplets of density $\rho_{\text{drop}}' = 1000\text{kgm}^{-3}$. In human respiration, the exhaled droplets have diameters $2d'$ in the range 0.5 $\mu m$ to 2000 $\mu m$. For a human breathing at rest, their average volume flux is in the range $Q_1' = 5$-8 L min$^{-1}$: these values of flow rate are similar to those in previous studies which reports 13 litre/min for breathing, and the typical speed of a jet in normal breathing conditions is of the order of $U' = 1 \text{m s}^{-1}$. In violent respiratory events, such as sneezing or coughing, these values could be significantly higher. Finally, the extraction unit is located a distance of $|x_0'| = 0.2 \text{m}$ from the person. These quantities are summarised in Table II.

![Table II. Physical quantities for extraction.](image)

<table>
<thead>
<tr>
<th>Quantity Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U'$ Breath jet velocity</td>
<td>1</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\rho_{\text{air}}'$ Density of air</td>
<td>1.149</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\rho_{\text{drop}}'$ Density of droplet</td>
<td>1000</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\nu_{\text{air}}'$ Viscosity of air</td>
<td>$16.36 \times 10^{-6}$</td>
<td>m$^2$ s$^{-1}$</td>
</tr>
<tr>
<td>$Q_1'$ Volume influx</td>
<td>6.5</td>
<td>L min$^{-1}$</td>
</tr>
<tr>
<td>$Q_2'$ Volume outflux</td>
<td>2600</td>
<td>L min$^{-1}$</td>
</tr>
<tr>
<td>$</td>
<td>x_0'</td>
<td>$ source-sink distance</td>
</tr>
</tbody>
</table>

Based on these numbers, the non-dimensional parameters that govern the trajectory of the particle are determined to be $R = 0.00115$, $Re = 12,225$, $1.70 \times 10^{-12} < St < 0.017$, $0.067 < A < 6.76 \times 10^8$, $\Lambda = 0.00068$, and $|g| = 1.96$ where the ranges indicate the values attained for the stated droplet size distribution. The parameter $\gamma$ relates the flux of the extraction unit to the flux of a human’s breath, and its effect will be examined. In particular, if we suppose that the envisaged extraction unit has a volume flux approximately equal to that of a standard vacuum cleaner (100 cfm), then we can approximate that $\gamma \approx 400$. In Figure 7, we show the efficacy of such extraction for a range of $St$. Extraction is very effective at low $St < 10^{-4}$, however for $St > 4.2 \times 10^{-4}$, such extraction is ineffective. This upper bound of the Stokes number corresponds to water droplets of diameter 0.16 mm. Droplets larger than this will not be collected by extraction. In the nomenclature of Section IV B, the effective range of extraction corresponds to non-ballistic droplets.

V. DISCUSSION AND CONCLUSION

In this paper, we have presented a simplified mathematical model for droplet dispersion from a source and in the presence of gravity, and for $St \ll R$, droplets behave as ideal tracers and the maximum distance that they can travel before being extracted is a function of $\gamma$ only. In this case, there are two (source, and sink if $\gamma = 1$)
or three (source, sink, and saddle if $\gamma > 1$) fixed points. The fixed points in this study are co-linear, and the position of the saddle depends on $\gamma$ alone, for any given distance between source and sink. For moderate $St$, the droplets’ inertia carry them far away from the source until they are slowed down by drag forces and pulled into the sink. In this case, the maximum distance that droplets can travel is given by $R/\gamma$.

When gravity effects are taken into account, the saddle point for $St \ll R$ is no longer co-linear but moves on an arc, clockwise about the source, and a fourth fixed point (saddle) emerges approximately below the sink fixed point. For fixed $\gamma$, this fixed point moves closer to the source as the magnitude of gravity is increased. In this case, there is a set of trajectories that are pulled away from the sink by gravity. For moderate $St$, gravity plays an increasingly important role, and there is a critical value of gravity that pulls all trajectories vertically downwards away from the source. For yet larger $St$, the trajectories adopt a ballistic trajectory, with even those that travel close to the sink not being pulled in.

We included simulations relevant to human respiration, as well as simulations to inform the development of an aerosol extractor for use in clinical settings. These models can help to guide recommendations on maximum safe distances between source and sink. Additionally, these models provide a better understanding of the behaviour of individual droplets of various sizes, that may be present in a wide range of aerosols contaminated with viruses or other pathogens. This may help clinicians to make better informed decisions regarding safety while performing aerosol generating procedures; and in their choices of the type of PPE they wear. Lastly, these models provide a basis upon which aerosol and droplet contamination from a wide range of surgical, medical, dental and veterinary AGPs can be modelled, while taking into account airflows in confined clinical spaces. In this case, we found that for $St \leq 10^{-4}$, all of the aerosol is extracted and that gravity has minimal effect, this $St$ corresponds to droplets with approximate diameter equal to 0.08 mm. Droplets larger than this are affected by gravity, and for $St = 10^{-2}$, corresponding to droplets equal to 0.78 mm, none of the droplets are extracted. Such large droplets would be typically captured by of personal protective equipment (PPE), such as FFP1 masks, which have pore sizes typically smaller than 1 $\mu$m, corresponding to a droplet Stokes number of about $10^{-7}$.

We determined the maximum range of droplets ejected from the source in the absence of a sink, and found that the range is minimised for intermediate-sized droplets. We find that in human respiration, this pertains to droplets within the observed range of ejected droplets. This could have implications for the interpretation for data coming from experiments on biological subjects. In particular, those that attribute observed bi- and tri-modal droplet dispersion to biological functions. Our studies suggest that the bi-modal nature of the curve is a function of the droplet’s Stokes number and not necessarily linked to a specific biological function.

In our model, we neglected the Basset history term and the added mass term in the Maxey-Riley equation. These Basset history term is of significant importance for bubbly flows, where it can account for a quarter of the instantaneous force on a bubble[23]. Generally speaking, for $R \ll 2/3$, this term can be safely ignored for small and intermediate-sized droplets. Recent studies have also shown that neglecting it in modelling of raindrop growth leads to a substantial overestimate of the growth rate of the droplet. Hence, for the solutions that become ballistic, we expect that such trajectories would be influenced by the Basset history term, and should be included. To do this efficiently, there is a very promising method developed recently[24]. Since this is not the focus of our study (such droplets can be captured by other forms of PPE), we do not perform such a study here.
ACKNOWLEDGEMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.


Dynamics of spherical droplets in source-sink pair flow fields

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Dynamics of spherical droplets in source-sink pair flow fields


