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Off-centre impact on a horizontal fibre

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Abstract. Fibre filters that consist of a network of randomly oriented thin fibres are commonly used to recover the liquid phase from an aerosol. During the filtration process, drops of the aerosol impact the solid fibres of the filter. If the impact velocity is smaller than a threshold velocity V_c , the drop is entirely captured by the fibre whereas if the velocity is larger than V_c , only a small portion of fluid remains trapped on the solid fibre. While this threshold velocity has been determined when the impact is centred – i.e. when the trajectory of the drop and the axis of the fibre do intersect – fewer studies are related to off-centre impact. Here, we focus on the influence of the relative position of the drop and the fibre on the impact. For velocity larger than V_c , we vary the eccentricity and measure the ability of the fibre to retain the liquid phase. Quite surprisingly, we show that off-centre impact situation enhances the ability of the fibre to capture a portion of the drop.

1 Introduction

Fibre filters are commonly used to recover the solid or liquid phase from polluting aerosols in deserted areas [1–3]. These filters consist of networks of randomly oriented solid fibres that capture the liquid phase while the gaseous phase passes through them. Their aim is twofold: first to capture the largest amount of liquid on the fibres then to slow down the fragments of the liquid drop that are ejected out of the fibre. The efficiency of such filters can be defined as the percentage of captured liquid during the impact. Its optimization – that is of obvious practical interest – is a difficult task for different reasons. First, it is time-dependent; as the mass of liquid collected within the filter increases, the liquid droplets trapped on the fibre can coalesce and reorganize in thin films that eventually clog the filter [4,5]. In this study, we only focus on the early stage of the filtration process where the fibres are still dry, thus those long time behaviours are not considered here. Then, the characteristics of the filter depend on different lengthscales: the typical distance between the fibres of the filter (denoted as λ), the mean radius R_i of the drops of the aerosol and b the fibre radius. The efficiency of the filter, which is a subtle interplay between these lengthscales, therefore depends on a wide range of parameters [6]. In this work, we only consider the limit where the typical distance between the fibres is larger than the typical radius of the impacting drop and the fibre. We therefore focus on the impact of a single drop on a horizontal fibre that is a paradigm for fibre filtration. It has recently been shown that a drop can be entirely captured by the fibre if the impact velocity is smaller than a threshold velocity V_c called the velocity of capture [7]. However, this issue has only been addressed in the case of centred impact, when the trajectory of the falling drop and the axis of symmetry of the fibre intersect [7]. Yet, this situation of centred impact is restrictive when considering the practical problem of fibre filtering: it is very unlikely to observe perfectly

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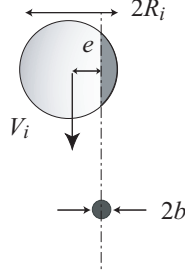


Fig. 1. Sketch of the experiment: a liquid drop of radius R_i hits a horizontal fibre of radius b with a velocity V_i . The impact is off-centre. The distance between the trajectory of the centre of mass of the drop and the axis of the fibre is the eccentricity of the impact e .

centred impact during the process. Therefore, to gain better understanding of what happens during the filtration, we consider off-centre impact where the drop trajectory and the fibre axis do not intersect. In particular, we focus on the amount of the initial drop that can be trapped by the fibre and compare centred and off-centre impact situations. Quite surprisingly, we observe that centred impact is not the most favourable situation for capturing liquid. We quantify this maximum as a function of the impact velocity and the distance between the centre of mass of the drop and the axis of the fibre.

2 Experimental set-up and observations

A free falling drop of radius R_i and of volume Ω_i impacts a stainless steel fibre of radius b ($b = 250 \mu\text{m} \pm 20 \mu\text{m}$) at a velocity V_i as sketched in Figure 1. Drops of radius $R_i = 1250 \mu\text{m}$ (i.e. $\Omega_i = 8 \text{ mm}^3$) are released from a nozzle placed above the fibre, at a distance which can be varied between 0.5 and 10 cm, which yields to velocity in the range of 10 cm/s to 150 cm/s. The eccentricity of impact e – that is the distance between the centre of mass of the drop and the fibre axis – can be precisely controlled using microcontrollers.

The whole process is recorded using a high speed camera with typically 1000 frames per second and an exposure time of $1 \mu\text{s}$. Distilled water at room temperature that partially wets the fibre is used for the drops. Surface tension and density are noted γ and ρ . We experimentally determine that for $\Omega_i = 8 \text{ mm}^3$, the critical velocity V_c required to capture a drop when the impact is centred ($e = 0$) is $V_c = 0.42 \text{ m/s}$. In this work, we only consider impact velocity larger than 0.42 m/s .

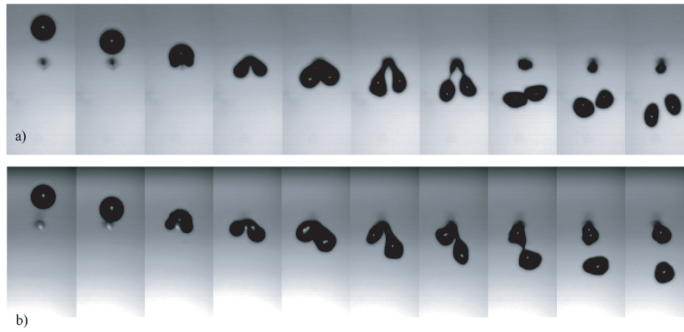


Fig. 2. Set of pictures taken every 2 ms showing a 2.5 mm diameter drop impacting a $500 \mu\text{m}$ diameter fibre at $V_i = 0.6 \text{ m/s}$. (a) Centred impact: the impact is nearly centred ($e < 10 \mu\text{m}$) and the drop is sliced in two lobes of equal volume. (b) Off-centre impact: the drop is sliced in two lobes of different volumes. The largest one detaches from the fibre while the small one remains trapped onto the fibre.

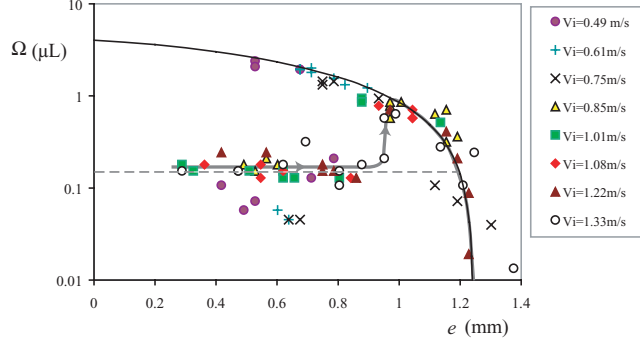


Fig. 3. Ω the volume of liquid trapped by the fibre after the impact as a function of e the impact eccentricity for different impact velocities. The thick black line corresponds to equation (1).

In Figure 2(a), we show a sequence of images where a water drop hits the fibre nearly in its centre ($e < 10 \mu\text{m}$) with a velocity of 0.57 m/s. It can be observed that the fibre slices the drop into two independent lobes of relatively equal volume. Those two lobes – that do not coalesce during the whole sequence – eventually detach from the fibre. The volume of liquid trapped by the fibre, only represents a tiny fraction of the initial drop volume Ω_i . An identical drop impacting with the same velocity on a fibre left-shifted of $800 \mu\text{m}$ is shown in Figure 2(b). We also observe the formation of two independent lobes but their volumes are logically uneven: we estimate the volume of the right lobe to 0.75 of the volume of the initial drop while the volume of the left lobe only represents 0.25. In that asymmetric case, the fibre retains entirely the small lobe while the large one is ejected down the fibre. The volume of liquid collected by the fibre is therefore larger in Figure 2(b) than in Figure 2(a). Identical experimental features can be observed in numerical simulations reported by Pasandideh-Fard et al. [8].

Using image analysis we accurately measure Ω the volume of liquid that remains attached on a fibre after impaction of a $8 \mu\text{L}$ drop falling on the fibre with a velocity between 0.49 m/s and 1.33 m/s. In Figure 3, Ω is displayed as a function of the eccentricity of impact e for different initial velocities V_i . In a logarithmic representation of the results, all the data collapse on two different branches that coexist for $400 \mu\text{m} < e < 800 \mu\text{m}$. The first branch (denoted as (1) and outlined with a dashed horizontal line in Figure 3) only exists for small values of eccentricity $e < 800 \mu\text{m}$. On this branch, the volume captured by the fibre is constant – in the order of $0.02 \mu\text{L}$ for all values of the impact velocity V_i – and equal to the volume trapped by the fibre for centred impact. The second branch (denoted as (2) and outlined with a thick black line) corresponds to larger values of e ($e > 400 \mu\text{m}$). It differs from branch (1) for several reasons. First, the volume of liquid collected by the fibre exhibits a sharp decrease as e is increased: it drops from $2 \mu\text{L}$ for $e = 400 \mu\text{m}$ to $0.02 \mu\text{L}$ for $e \sim 1 \text{ mm}$. Then, the plain line in Figure 3 does not correspond to a fit of the experimental data but to the volume of a spherical cap of radius R_i and of height $R_i - e$. The volume of such a spherical cap – which appears in dark grey in Figure 1 – is given by:

$$\Omega = \frac{\pi}{3}(R_i - e)(2R_i^2 + R_i e - e^2). \quad (1)$$

For e ranging between 0.5 and 1.3 mm, the agreement between the experimental data and equation (1) is very good without any adjustable parameters. Under our wetting conditions, the stainless fibre slices the water drop into two different parts and as the eccentricity of the impact increases, the volume of the smallest part decreases until it vanishes for $e \approx R_i$ as can be seen in Figure 3. For $e < 0.3 \text{ mm}$, we observe that the thick black line intersects the y -axis for $\Omega = 4 \mu\text{L}$. Indeed, when the axis of the fibre and the trajectory of the free-falling drop intersect ($e = 0$), the drop is cut into two lobes of equal volume $\Omega = \Omega_i/2 = 4 \mu\text{L}$. However, no experimental data correspond to the fit for those values of e . The impact velocities that we consider here, are too large to capture such large portion of the initial drop.

To gain better understanding of the processes at stake, it is worthwhile following how Ω varies for increasing value of e for a given impact velocity. For clarity, the set of data

$V_i = 1.08 \text{ m/s}$ is outlined in Figure 3 with a grey line. For small value of e , Ω follows the first branch, until a critical value $e^* = 1 \mu\text{m}$ is reached where the volume trapped by the fibre is given by branch (2). It reaches a maximum Ω^* for a critical value of eccentricity e^* then it decreases for $e > e^*$. We stress that this hump-shaped curve is not specific of the data corresponding to $V_i = 1.08 \text{ m/s}$ and is observed for all the velocities. Nevertheless, the values of Ω^* the maximal volume of liquid that can be trapped by the fibre and e^* depend on the impact velocity. In particular, the larger the impact velocity, the smaller Ω^* and the larger e^* .

3 Discussion

To understand those data, we use the framework developed for centred impact situation described in [7]. During the impaction phenomena, the drop undergoes several forces. Capillary forces are responsible for the drop sustentation while drag forces induce a dissipation that can possibly stop the drop. The balance between these two forces with both gravity and inertia yields to a relation between V_i and Ω_c , the volume of the largest drop falling at V_i that can entirely hang on the fiber [7]:

$$V_i = V_M \left[\frac{e^{kR_M/R_i} - 1}{kR_M/R_i} \right]^{\frac{1}{2}} \left[\left(\frac{\Omega_M}{\Omega_i} \right)^{\frac{2}{3}} - \left(\frac{\Omega_c}{\Omega_M} \right)^{\frac{1}{3}} \right]^{\frac{1}{2}} \quad (2)$$

where Ω_M , V_M and k depends on γ , ρ , g , C_d and b such as $\Omega_M = 4\pi/3R_M^3 = 4\pi b(\gamma/\rho g)^{-1}$, $V_M = \sqrt{4gR_M}$ and $k = 12C_db/(\pi R_M)$ [7]. In our experiment V_i varies between 0.49 and 1.33 m/s; using equation (2) this yields to Ω_c between 0.3 and 5 mm³. Yet, the initial volume of the drop Ω_i is equal to 8 mm³, thus the volume of the impacting drop is always larger than the critical volume Ω_c . This is in agreement with our previous observations: in the range of velocity V_i considered here, we never see a drop that would be entirely captured. Only a fragment of them remains stuck on the fibre.

The eccentricity of impact is directly related to the size of the two drop fragments that are formed after the impact of the drop on the fibre. If the volume of those fragments is larger than Ω_c – the critical volume of capture that is given by equation (2) – only a small fraction of liquid remains captured on the fibre. In that case, the volume captured by the fibre is proportional to hbR_i where bR_i is the surface of the fibre wetted by the drop and h is the thickness of the Landau Levich liquid film on the fibre. This volume which is typically in the order of 0.1 μL corresponds to the branch (1) of figure 3. As the eccentricity of the impact is gradually increased, the volume of one of the fragments eventually happens to fall down the critical volume Ω_c . Then, the capillary forces are large enough to sustain this fragment onto the fibre and it remains trapped as depicted in figure 3 by the branch (2). The transition between the two states (trapped or released) can be rather abrupt as highlighted in figure 3 by the grey line. As soon as this transition has occurred, any further increase of the eccentricity only lead to a decrease of the volume of the smaller fragment that always remains trapped onto the fibre. This holds up to a value of the eccentricity larger than the drop radius. In that case, the drop falls without touching the fibre.

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