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# Drops impacting inclined fibers

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ABSTRACT

Mats of fibers are often used to capture liquid drops, such as in filters or in fog's nets. It is desired to optimize the efficiency of capture, in particular in the limit of drops larger than the fibers, for which filters remain highly permeable. Here we show that the efficiency of capture is dramatically increased by tilting the fibers: then, the velocity $V^*$ below which a drop is fully captured is made much larger; moreover, the tilt maximizes the liquid volume left on the fiber when the impact velocity exceeds $V^*$.



## 1. Introduction

Assemblies of fibers are often used for capturing the liquid fraction of an aerosol, as it passes through such filters. Fog's nets, for example, are deployed in countries such as Chile, Peru and South Africa, with a rate of recovery of the order of 30 L/m$^2$ and per day [1,2]. In other cases, it is desired to stop a liquid pollutant contained in an atmosphere, and fiber filters can be used for this purpose, without preventing the gaseous component from flowing [3]. Another application concerns the making of glasswool used for insulating houses: drops of glue are sprayed on the freshly drawn glass threads in order to induce irreversible sticking and entanglement of the fibers, leading to the construction of thick insulating materials. In all these cases, the threads must stop incoming liquid drops, even in the limit where the drop size exceeds the fiber radius [4–6]. We demonstrate in this paper how the capture can be efficiently improved by playing on the angle at which the drop hits the fiber.

The quality of wetting might also matter, but we will mostly restrict our study to the case of wetting liquids, for which the shape of the drops or films was discussed in the case of horizontal [7–9] and tilted or vertical fibers [10–14]. A small wetting drop is axisymmetric. However, gravity will deform it when its radius $R$ approaches the millimeter-size capillary length $\kappa^{-1}$. (Let us recall that $\kappa^{-1}$ is $\sqrt{\gamma/\rho g}$, denoting $\rho$ and $\gamma$ as the liquid density and surface tension.) Such "large" drops can still hang on horizontal fibers (of radius $b$), when the gravitational force balances the capillary force, of the order of $\rho g R^3$ and $\gamma b$, respectively. This yields a maximum drop size $R_M$ scaling as $\kappa^{-2/3} b^{1/3}$, which is typically much larger than the fiber radius $b$ [3,4]. Because the drop is held back by two menisci, the (maximum) capillary force $f_c$ in this geometry can be approximated by [6]:

$$f_c = 4\pi\gamma b \qquad (1)$$

which is twice larger than the force allowing a drop to hang as the bottom of a fiber of radius $b$, since we only have one meniscus in the latter case. We thus get a maximum drop radius of $3^{1/3}\kappa^{-2/3}b^{1/3}$, as confirmed in a recent series of experiments [6]. A drop of silicone oil ($\kappa^{-1}$ = 1.5 mm) will hang to a thread of radius $b$ = 100 μm provided that its radius $R$ is smaller than 1 mm: in this example, the drop can be ten times larger than the fiber on which it holds on!

## 2. Velocity of capture

We place a nylon fiber ($b$ = 250 μm) between a vertical wall and a horizontal rod and tighten it by attaching a plumb at its end. The rod can be displaced vertically in order to change the tilt angle $\alpha$ of the fiber, which can be varied between 0° and 80° relative to the horizontal. A syringe filled with silicone oil (of surface tension $\gamma$ = 20 mN/m, density $\rho$ = 915 kg/m$^3$ and viscosity $\eta$ = 5 mPa s) is placed above the fiber and aligned with it: impacts are centered, an important feature since off-centered impacts perturb the capture mechanism [15]. The impact velocity $V$ is modified by displacing vertically the syringe. We first describe what happens when keeping the tilt angle fixed (here at $\alpha$ = 45°), and varying $V$ (Fig. 1).

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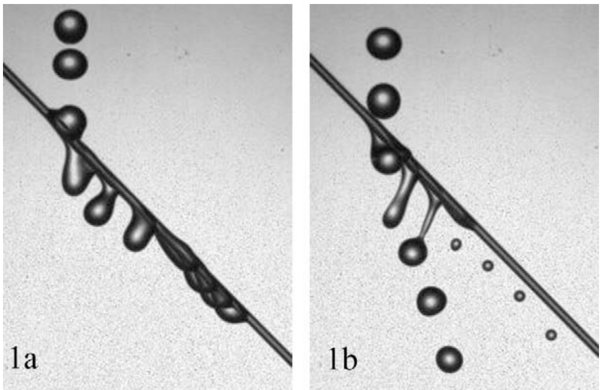


**Fig. 1.** Impact of a drop of silicone oil of radius $R = 1$ mm, surface tension $\gamma = 20$ mN/m, density $\rho = 915$ kg/m$^3$ and viscosity $\eta = 5$ mPa s on a nylon fiber of radius $b = 250$ µm inclined by 45°. In (a), the interval between pictures is 10 ms, the impact velocity $V$ is 30 cm/s and the whole drop is captured by the fiber. In (b), the interval between pictures is 7 ms and the impact velocity is 47 cm/s. Owing to this larger velocity, the drop is not fully captured. However, it follows the fiber on about 1 cm, where it leaves part of its mass. A satellite forms as the drop detaches, and then falls down.

As seen in Fig. 1, the capture efficiency depends on the drop speed. At low impact speed ($V = 30$ cm/s, Fig. 1a), the drop sticks to the fiber and then slowly runs down along it, leaving a film behind, as classically observed for wetting liquids [11]. At a larger impact speed ($V = 47$ cm/s, Fig. 1b), the drop crosses the fiber and gets deflected. Comparing the drop(s) volumes before and after impact shows that a significant quantity of liquid is left on the thread (in this example, 40% of the impacting volume is transferred to the fiber), as resulting from the centimeter-size descent along the fiber before detaching. It is straightforward to deduce from series of such experiments the threshold velocity $V^*$ below which a drop is fully captured. We measured $V^*$ as a function of $\alpha$, the tilt angle of the fiber (Fig. 2). It is found that inclining the fiber deeply affects the capture: the velocity $V^*$ is multiplied by a factor larger than 5 as $\alpha$ increases from 25° to 80°.

Four forces are likely to act on the drop: on the one hand, gravity and inertia favor the crossing of the fiber; on the other hand, viscous and capillary forces tend to slow down (and even stop)

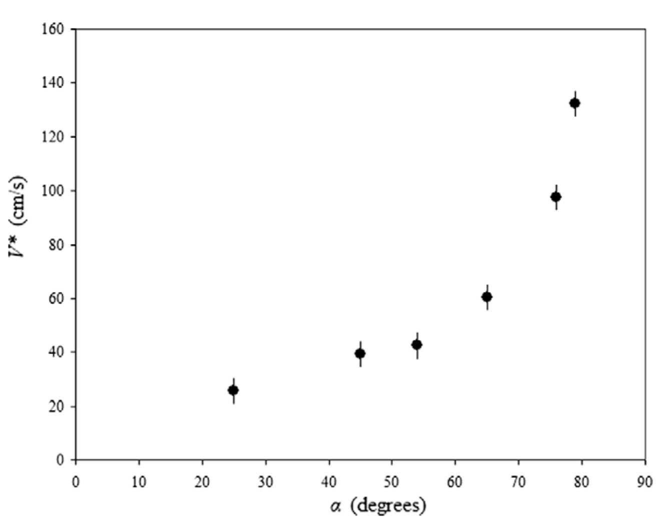


**Fig. 2.** Critical velocity of capture of drops of silicone oil ($R = 1$ mm, $\gamma = 20$ mN/m, $\rho = 915$ kg/m$^3$ and $\eta = 5$ mPa s) below which the drops are fully captured by a nylon fiber ($b = 250$ µm), as a function of the tilting angle $\alpha$ (measured from the horizontal) of the fiber. It is observed that the capture is made much more favorable when inclining the fiber.

the drop. A comparison between inertia (of the order of $\rho V^2/R$) and gravity ($\rho g$) implies the Froude number $Fr = V^2/gR$. For usual impacts, the velocity is at least 10 cm/s, which makes $Fr$ always larger than unity. In our experiments for example, with $V \approx 30$ cm/s and $R \approx 1$ mm, we get $Fr \approx 10$. The comparison between viscosity and capillarity is expressed by the capillary number $Ca = \eta V/\gamma$. In most applications, water or aqueous solutions are used and $Ca$ is expected much smaller than unity, as in our experiments ($\eta = 5$ mPa s, $V \approx 30$ cm/s and $\gamma = 20$ mN/m) where it is less than $10^{-2}$.

Hence the capture dynamics will usually result from a balance between inertia and capillarity. We denote $M$ as the mass of the drop, and $x$ and $z$ as the axis along and perpendicular to the fiber. We project Newton's law on the $z$-axis, since this is the direction on which the capillary force acts to hold the drop. Using Eq. (1) (which gives the maximum capillary force, that is, the one relevant at detachment), this can be written: $M\mathrm{d}^2z/\mathrm{d}t^2 \approx -4\pi\gamma b$, which yields the trajectory of the south pole of the drop (which hits the fiber at $t = 0$):

$$z = -2\pi\gamma b t^2/M + V\cos\alpha t \tag{2}$$

The extremum of $z(t)$ is $z_M = \rho V^2R^3\cos^2\alpha/6\gamma b$. Hence a natural criterion for the capture: either $z_M$ is smaller than $2R$, the drop diameter, and the drop stops before detaching (full capture); or it is larger, and the drop still moves when it detaches and gets again accelerated in the field of gravity. This yields a threshold velocity $V^*$ which writes:

$$V^* = V_o/\cos\alpha \tag{3a}$$

with:

$$V_o = (12\gamma b/\rho R^2)^{1/2} \tag{3b}$$

The capture velocity $V^*$ is thus found to depend critically on the tilt angle $\alpha$, since it diverges as $1/\cos\alpha$ when the fiber tends to be vertical ($\alpha = 90°$). $V^*$ is normalized by the maximum capture velocity $V_o$ on an horizontal fiber, which slowly depends on the physical parameters it contains [6]. For millimetric drops on fibers of radius around 100 µm, $V_o$ is expected to be 20 cm/s, and it becomes about 1 m/s when dividing the typical scales $b$ and $R$ by 10. $V_o$ is modest, compared to the typical velocities of drops in free fall or to wind velocities, if we think of a fog's net. Thus, it is practically crucial to amplify it by the geometric factor $1/\cos\alpha$, which is approximately 6 when $\alpha$ is 80°. We tested quantitatively Eqs. (3a) and (3b) by measuring the capture velocity $V^*$ for various liquids: the silicone oil used in Fig. 2, and a mixture of water and glycerol of similar viscosity and much larger surface tension ($\gamma = 67$ mN/m), providing a different wettability (a drop of this liquid meets a nylon fiber with a contact angle of 45°, instead of 0° for the silicone oil). We also tried an aqueous solution of similar surface tension but five times less viscous ($\eta = 1$ mPa s).

All the results are displayed in Fig. 3, where the capture velocity normalized by $V_o$ is plotted as a function of $1/\cos\alpha$. The data all collapse on the same straight line passing through the origin, as expected from Eq. (3). The agreement is even found to be quantitative since the line is observed to have a slope 1.01 ± 0.04, without any adjustable parameter.

## 3. Wetted distance

It is also worth describing what happens when the drop crosses the fiber ($V > V^*$). As clearly seen in Fig. 1b, the fiber may be coated by the liquid on a length much larger than the drop diameter. We show in Fig. 4 the detail of a sequence of impact, where a drop of silicone oil ($R = 1$ mm, $\eta = 5$ mPa s) hits a fiber inclined by 65° at $V = 61$ cm/s, a velocity just larger than $V^*(65°) = 60$ cm/s. We

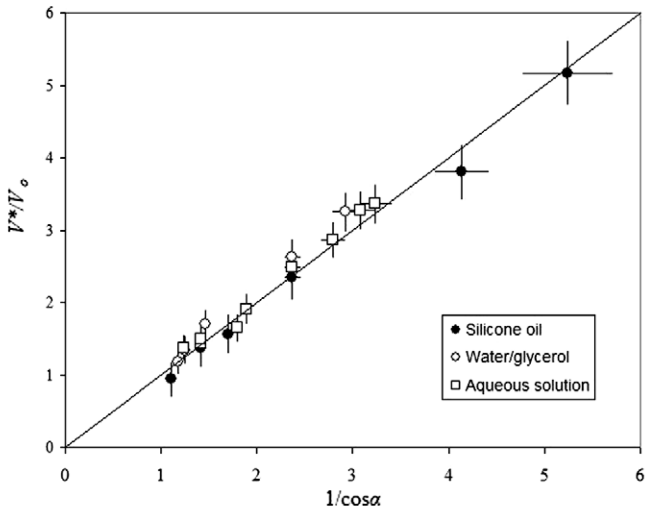


**Fig. 3.** Critical velocity of capture $V^*$ of drops falling on a nylon fiber ($b = 250$ μm) tilted by an angle $\alpha$. The velocity is normalized by a characteristic velocity $V_o$ that depends on the liquids and on the dimensions of the drops and of the fiber, as defined in Eq. (3b) ($V_o = (12\gamma b/\rho R^2)^{1/2}$). Experiments are performed with silicone oil (full circles; $R = 1$ mm, $\gamma = 20$ mN/m, $\rho = 915$ kg/m$^3$ and $\eta = 5$ mPa s), a 50/50 mixture of water and glycerol (empty circles; $R = 1.15$ mm, $\gamma = 67$ mN/m, $\rho = 1100$ kg/m$^3$ and $\eta = 6$ mPa s), and an aqueous solution (squares; $R = 1.1$ mm, $\gamma = 70$ mN/m, $\rho = 1000$ kg/m$^3$ and $\eta = 1$ mPa s). Eq. (3) is drawn with a full line.

subtract the first image to the following ones, which allows us to improve the contrast and to emphasize the dynamical events. The drop first crosses the fiber (first three images), and then slides along it while elongating, until it pinches off and detaches.

Fig. 4 makes clear that the distance $L$ wet after impact can be measured accurately. We also notice (as done in Fig. 1b) that the drop volume is significantly smaller after the crossing. We can deduce from such sequences the proportion of liquid $\Delta\Omega/\Omega_o = (\Omega_o - \Omega)/\Omega_o$ left on the fiber, denoting $\Omega_o$ and $\Omega$ as the drop volume before and after the crossing. We report in Fig. 5 the values of $L$ and $\Delta\Omega/\Omega_o$ as a function of the impact velocity $V$, for a fiber of radius $b = 250$ μm inclined by 45°.

Below threshold $V^*$ of capture, we have: $\Delta\Omega/\Omega_o = 1$, and the wetted distance is the whole fiber length. Above $V^*$, it is observed that the wetted length and volume of liquid on the fiber are roughly independent of the impact velocity. The proportion of liquid $\Delta\Omega/\Omega_o$ left on the solid is far from being negligible, as it is for a drop crossing a horizontal fiber [6] – since it is found here to represent about one-third of the impacting drop. Hence the inclination also influences (and favors) the capture of liquid in the regime of partial capture, compared to what can be observed for a horizontal thread.

In the limit $V > V^*$, the Weber number associated with impact is larger than unity, and we can neglect the capillary force (Eqs. (1) and (2)) responsible for the drop arrest in the opposite limit. Since the viscous force can still be neglected, as emphasized earlier, we mainly assume that the drop speed remains of the order of $V$ all along the impact on the fiber. Hence, the problem becomes mainly geometric, as sketched in Fig. 6.

The movement can be decomposed in two phases, as seen in Figs. 1, 4 and 6(b). In the first phase, the drop crosses the fiber; then, it elongates owing to its inertia, which eventually breaks and detaches it. For $b \ll R$, the vertical distance travelled by the drop in the first phase can be written: $2R/\cos\alpha$, which provides a crossing time $\tau_1 = 2R/V\cos\alpha$. The length of solid in contact with

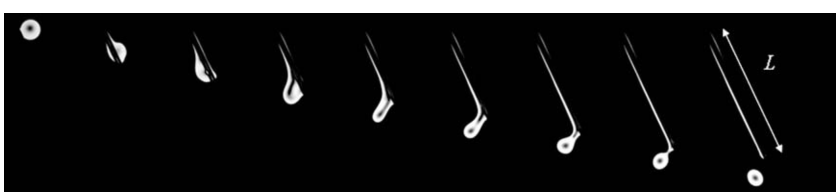


**Fig. 4.** Impact of a drop of silicone oil ($R = 1$ mm and $\eta = 5$ mPa s) on an inclined fiber ($\alpha = 65°$) at a velocity $V = 61$ cm/s slightly larger than the capture velocity $V^* = 60$ cm/s. For each image, we subtracted the first image, which emphasizes all the dynamic events. Firstly, the drop crosses the fiber; then, it slides below it while elongating, until its length allows it to detach. The wetted distance $L$ is much larger than the drop diameter, which shows that tilting the fiber considerably enhances the capture of liquid, even in the regime $V > V^*$. Interval between successive images: 3.5 ms.

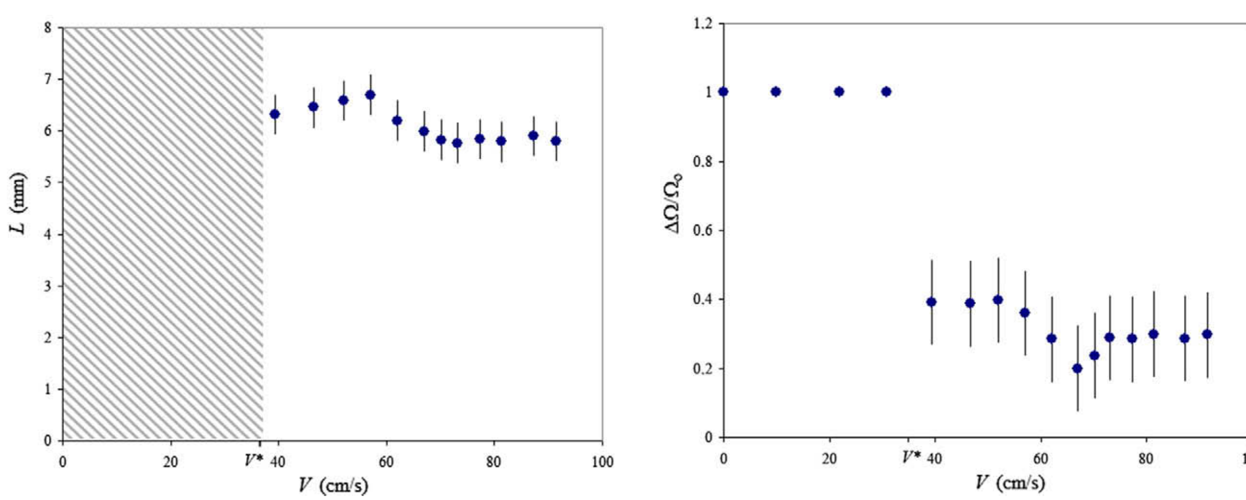


**Fig. 5.** (a) Distance $L$ wetted by a drop of silicone oil ($R = 1$ mm and $\eta = 5$ mPa s) as it crosses and moves along a fiber inclined by $\alpha = 45°$, before detaching. For $V < V^*$, the liquid is captured by the solid, and $L$ is very large (not represented); for $V > V^*$, the wetted length hardly varies as a function of $V$. Its value is about three times larger than the drop diameter. (b) As a consequence of this extended contact, the proportion of liquid left on the fiber beyond $V^*$ is non-negligible, when tilting a fiber: it is found here to be about one-third of the impacting drop.

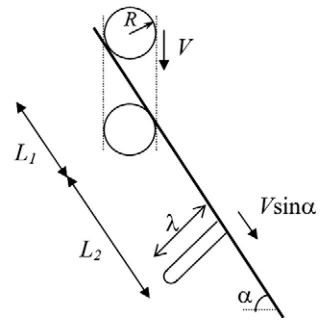


**Fig. 6.** A drop crossing an inclined thin fiber at $V > V^*$: the drop first crosses the thread (in a time denoted as $\tau_1$), and then it elongates before breaking (in a time denoted as $\tau_2$). We call $\ell$ and $r$ the length and radius of the cylindrical elongated drop at $t = \tau_2$.

the liquid during this phase is (geometrically) $L_1 \approx 2R/\cos\alpha$. In the second phase, the drop remains attached to the fiber owing to its viscosity and surface tension, and it elongates at a characteristic velocity $V\cos\alpha$, until it becomes long enough to pinch off. The Plateau criterion can be used at this point: the drop breaks when its length $\ell$ exceeds its perimeter $2\pi r$. Applying volume conservation, this criterion can be written: $\ell > (16\pi^2/3)^{1/3} R$, i.e. approximately 3.75$R$. We thus expect a detachment time $\tau_2$ of the order of $(16\pi^2/3)^{1/3}R/V\cos\alpha$. This time is typically 20 ms, larger than the Rayleigh time $(\rho R^3/\gamma)^{1/2}$ (about 5 ms) necessary to pinch the drop [16].

Since the drop is drawn along the fiber at a speed $V\sin\alpha$, the corresponding wetted length is $L_2 \approx V\sin\alpha\ \tau_2 \approx (16\pi^2/3)^{1/3}R\tan\alpha$. On the whole, the wetted length $L = L_1 + L_2$ should be given by the expression:

$$L = 2R/cos\alpha + (16\pi^2/3)^{1/3}R\tan\alpha \quad (4)$$

This length is indeed independent of the impact velocity, and it depends dramatically on the tilting angle: $L$ is minimum and (logically) equal to the drop diameter when the fiber is horizontal ($\alpha = 0$), and it (logically) diverges when the fiber becomes vertical ($\alpha = 90°$).

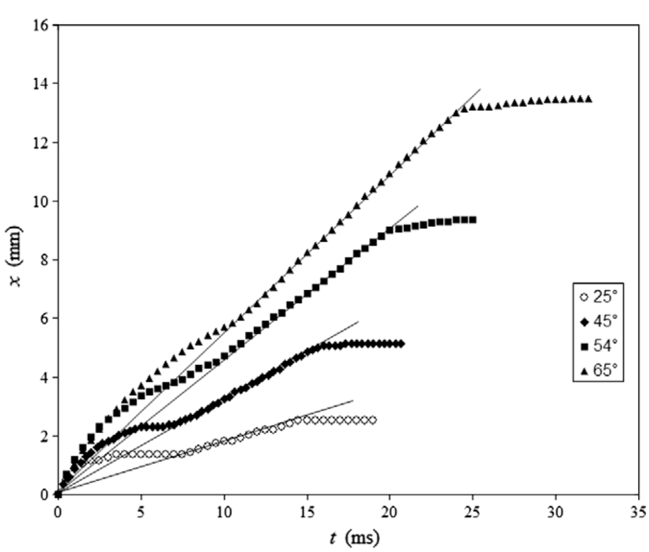


**Fig. 7.** Position of the front edge of a drop ($R = 1$ mm) of silicone oil ($\eta = 5$ mPa s) impacting at a velocity $V = 67$ cm/s a fiber (radius $b = 250$ μm) tilted by an angle $\alpha = 25°$, 45°, 54° or 65° ($V > V^*$, for all the angles). For each angle, three successive regimes are observed: first a complex behavior, corresponding to the crossing of the fiber; then, a regime of constant velocity (stressed by a thin line); then, the drop leaves the fiber at a time $\tau$ varying between 15 ms and 25 ms, depending on $\alpha$. The wetted length $L = x(\tau)$ can be deduced from the plot, and it is observed to increase with $\alpha$.

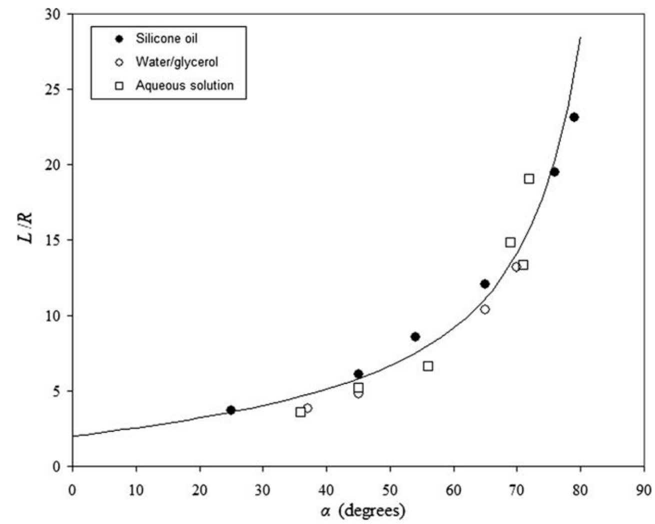


**Fig. 8.** Distance $L$ on which the drop coats the fiber before detaching ($V > V^*$) normalized by the drop radius $R$, as a function of the tilt angle $\alpha$, for various liquids on a nylon fiber of radius $b = 250$ μm. The symbols correspond to different liquids whose characteristics are given in Fig. 3. The solid line is the function $2/\cos\alpha + 3\tan\alpha$.

These simple ideas could be tested by filming the drop during the impact, as shown in Fig. 7, where we follow the position of the oil front along the fiber as a function of time, for different tilting angles and a given impact velocity $V = 67$ cm/s.

For each angle, this representation captures the different dynamic regimes discussed earlier. First, $x(t)$ is quite complex, with a rapid increase (corresponding to the impact) and a slowing down (corresponding to the crossing of the fiber); both the characteristic time $\tau_1$ and wetted length $L_1$ increase with $\alpha$ in this first regime, as expected from our discussion. Then, $x$ varies linearly with time (we stressed this behavior in Fig. 7 by drawing thin lines), allowing us to define a characteristic velocity $V_2$ of coating. $V_2$ is an increasing function of $\alpha$, and the time at which detachment occurs also depends on the tilting angle (later, $x$ hardly varies with time). All these features qualitatively agree with our discussion. In order to be more quantitative, we measured the total wetted length $L$, the quantity of practical interest, since it defines the efficiency of capture by the fiber in the regime where the solid does not fully stop the liquid. We report its variation as a function of $\alpha$ in Fig. 8.

As pointed out in Fig. 5a, the wetted length $L$ does not depend on the velocity (in the range we explored), which was checked for the different tilting angles we studied. Each data point in Fig. 8 is an average calculated over at least five impact velocities (with $V > V^*$), and it is plotted as a function of ⟨ for various liquids. $L$ is observed to increase by one decade when ⟨ goes from 25 to 80°. The behavior is very well captured by Eq. 4, which is drawn with a solid line with only one slight modification: the numerical coefficient of the second term ($\tan\alpha$) is 3 instead of approximately 3.75 in Eq. (4). Apart from this little difference, it is observed that Eq. (4) fits very well the data, whatever the nature of the liquid, and independently of their viscosities and surface tension, which confirms the geometric nature of the partial capture.

## 4. Conclusion

We showed here how tilting a fiber increases the efficiency of capture, when throwing a drop on this fiber. First, it was shown that the velocity $V^*$ below which the drop is fully stopped on the solid is dramatically increased with the tilt (divergence of this speed as $1/\cos\alpha$, where $\alpha$ is the tilt angle relative to the horizontal).

Secondly, it was reported that the length of fiber coated by the drop when it is not fully captured ($V > V^*$) is also impacted by the tilt: two effects contribute equally to the extended contact, that is, a geometric capture as the drop crosses the fiber, and a slowing down of the drop elongation before detachment.

These remarks might be useful for designing devices for which a capture is desired, such as glass fiber treatment or filtration. In the latter case, for example, placing the threads in such a way that the angle between the drop trajectory and the thread is minimized should provide a considerable increase of efficiency, in particular in the limit studied here ($b < R$), where the mutual distance between fibers can remain large enough to allow the driving fluid (often air, in an aerosol) to flow through the filter.

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