Controlling transport dynamics of confined asymmetric fibers

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 Abstract - Transport properties of particles in confining geometries show very specific characteristics as lateral drift, oscillatory movement between lateral walls or the deformation of flexible fibers. These dynamics result from viscous friction with transversal and lateral channel walls inducing strong flow perturbations around the particles that act like moving obstacles. In this paper, we modify the fiber shape by adding an additional, small fiber arm, which leads to T and L shaped fibers with only one or, respectively, zero symmetry axes and investigate the transport properties. For this purpose, we combine precise microfludic experiments and numerical simulations based on modified Brinkman equations. Even for small shape perturbations, the transport dynamics change fundamentally and formerly stable configurations become unstable, leading to non-monotonous fiber rotation and lateral drift. Our results show that the fundamental transport dynamics change with respect to the level of fiber symmetry, which thus enables a precise control of particle trajectories and which can further be used for targeted delivery, particle sorting or capture inside microchannels.
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• bility, but face problems of filter clogging or damaging of deformable particles. Recently microfluidic devices, rely-;; ing on specific transport properties, have been developed \geq to overcome these difficulties [1]. Inertial [2,3] or viscoelastic effects [4] can be used to focus particles at specific po- $\underline{\ }$ sitions inside channels and flexible particles are known to migrate away from bounding walls, leading for example to a cell free layer as observed in blood flow [5] or migration of flexible fibers in shear gradients [6]. Some microorganisms use passive reorientation mechanisms to move in gradients, either in the gravitational field (gravitaxis) [7] or in a gradient of viscosity (viscotaxis) [8]. In simple unbounded flows however, when inertia can be neglected, rigid particles only migrate across streamlines when symmetry is

This situation changes when particles are confined by bounding walls and act as moving obstacles to the flow. The induced strong flow perturbation leads to particle migration, as for example lateral drift observed for rigid fibers even at small Reynolds numbers [11]. Recently, theoretical models and experiments have been developed to describe such flows [10–14]. In particular, it has been shown that axisymmetric objects such as fibers or symmetric dumbbells (made of rigid spheres or drops) translate without rotation but drift at a constant angle, and may oscillate between the lateral walls of the channel [10] (Fig. 1(a,b)). Axisymmetric particles with fore-aft asymmetry, such as asymmetric dumbbells, will migrate toward the center of the channel, where they align with the flow [12,14], while laterally unconfined, asymmetric trimers rotate to reach an equilibrium angle [15]. Flexible fibers may be deformed by the viscous forces and will then rotate and align with the flow [6, 16]. In all these cases, the particle trajectory is strongly affected by the transversal confinement, which tunes the magnitude and distribution of the

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Fig. 1: Chronophotographies of transported fibers of different geometries. The fluid flows from left to right. As reported previously, straight fibers oscillate in the channel either through glancing (a) or reversing (b) [10]. T-fibers away from the lateral walls reorient toward a stable orientation parallel to the flow direction (c). L-fibers first rotate toward a stable orientation and then drift (d,e) until they are captured by the lateral wall (f). From top to bottom confinements are (a-b) 0.78, (c) 0.82, (d-e) 0.76, and (f) 0.72. Scale bars are 500 μm.

viscous force.

This situation bears some similarities with sedimenting particles where, in particular, there exists a coupling between translation and rotation that depends on the particle geometry, and particles that possess certain symmetries will exhibit specific motions. For example, axially symmetric objects, such as uniform rods, keep their orientation and merely translate without rotating [17]; an axisymmetric object that presents a fore/aft asymmetry, such as a dumbbell composed of spheres of different sizes, will rotate and align with the flow [18]. An asymmetric particle, as for example an L shaped particle, will rotate until it reaches a stable orientation, at which it will translate without rotating [7]. If in addition the chiral symmetry is broken, the coupling of translational and rotational movement leads to helical trajectories [19, 20].

We investigate these effects in detail by studying a model system consisting of a microfiber with increasing degrees of asymmetry transported in a microchannel. By adding a second arm to an initially straight fiber, we create and analyze, both theoretically and experimentally, Tshaped fibers with fore/aft symmetry and fully asymmetric L-shaped fibers. Examples of these fibers and corresponding chronophotographies of their transport dynamics are given by Fig. 1(c-f).

Straight fibers, which we will refer to as "I fibers" throughout this paper, oscillate between the lateral channel walls while transported downstream (Fig. 1(a,b)). In contrast the interplay of the long and short arms of the T and L fibers induces rotation even away from the lateral walls. T fibers rotate in most cases until aligned with the flow, with the small branch at the tail, and remain parallel to the flow while slowly migrating toward the center of the channel (Fig. 1(c)). L fibers rotate, either clock-



Fig. 2: (a) Geometry of an L-shaped fiber in the channel. The pressure-driven flow is sketched in blue. (b) Image treatment and definition of angles. Using MatLab procedures we derive from the picture of the particle its skeletonized shape (blue) and its center of mass (yellow circle). The scale bar is 200 μ m. (c) Evolution of the dimensionless rotation velocity $\dot{\theta} \ell_a / U_0$ with the angle θ for an L fiber with $\ell_a/h = 10$ and $\ell_b/h = 5$ for $\beta = 0.76$, far away from the lateral walls. The green circle indicates a stable fixed point and the red circle an unstable fixed point. (d) Experimentally observed evolution of the orientation angle θ as a function of the dimensionless time (dark blue). A fiber initially in its equilibrium orientation hits an obstacle (yellow stripe) and deviates from the equilibrium orientation. It then rotates back to the latter. The reorientation dynamics close to the equilibrium orientation (grey area) are well adjusted by an exponential fit (red curve in the zoom). The fitting method is detailed in the supplementary materials.

wise or anti-clockwise, until they reach an equilibrium angle which they keep while drifting toward the lateral wall (Fig. 1(d,e)). At the wall, two different scenarii can be observed. Fibers arriving with the sharp edge "rebound" off the wall, i.e. rotate until reaching their equilibrium angle and drift toward the opposite wall. Fibers arriving with the open side impact the wall and remain stuck at the wall (Fig. 1(d-f)).

In the following, we will primarily focus on L shaped fibers, being the most asymmetric objects, and complete the picture at the end of this letter by full trajectory diagrams in the configuration space of I, T and L fibers, revealing the fundamental difference between these three types of fibers and symmetries.

Problem formulation and methods. – Figures 2 (a,b) depict the configuration of a L fiber in the channel. The fiber is of square cross-section with width and height h, and ℓ_a and ℓ_b denote the lengths of the long and short arms, respectively. We will refer to ℓ_a/h and

 ℓ_b/h as the non-dimensional lengths or aspect ratios of the long and short fiber arms, respectively, and quantify the asymmetry by ℓ_a/ℓ_b , which is bounded by unity ($\ell_b = \ell_a$, symmetric fiber with two arms of equal length) and ℓ_a/h ($\ell_b = h$, I fiber). Starting from $\ell_a = \ell_b$, the asymmetry is first enhanced when decreasing the length of the short arm with respect to the long arm before the symmetry is restored when the short arm vanishes and a straight (I) fiber is attained.

The fiber is placed in a rectangular channel of height H and width W, and subjected to a pressure driven flow fully characterized by its mean velocity U_0 . The transversal and lateral confinements of the fiber are quantified by $\beta = h/H$ and $\xi = \ell_a/W$, respectively. As the channel is assumed to be of infinite length, the state of the fiber is completely described by the lateral position of its center of mass y and the orientation angle θ , together with the corresponding velocities \dot{y} and $\dot{\theta}$. Moreover we define the drift angle α by $\tan \alpha = \dot{y}/\dot{x}$. Note that there exists a mirror symmetry and that the mirror image of the fiber shown in Figures 2(b) corresponds to opposite fiber chirality.

The experimental methods, theoretical model, and numerical techniques are extensively described and verified in [10] and [16] and are outlined only briefly here. Fibers of controlled shape, position and confinement are fabricated using the stop-flow microscope-based projection photolithography method developed by Dendukuri et al. [21]: a pulse of UV-light passing through a mask illuminates the microchannel filled with a photosensitive solution (PEG-DA Mw=575 and Darocur 1173, viscosity $\mu = 68 \text{ mPa s}$) to create a rigid particle which is then transported in the non-crosslinked solution, with a pressure-driven flow imposed by a syringe pump (Nemesys, Cetoni). The presence of inhibition, i.e. uncured, layers of constant thickness $b = 6 \pm 1.6 \,\mu\text{m}$ in the vicinity of the channel walls [22] determines the fiber height h = H - 2b, and thus the transversal confinement β . For each channel height, we adjust the mask geometry to ensure a square cross-section of side h and a constant aspect ratio $\ell_b/h = 5$. With this method, the asymmetry ℓ_a/ℓ_b is tuned by changing the length of the long arm ℓ_a/h .

A two-dimensional Brinkman model supplemented by a model flow profile in the gap between the fiber and the transversal channel walls is utilized to determine the flow around the fiber and the resulting force and torque distribution on the fiber. Note that the velocity vector is uniquely determined by the particular state (y, θ) , as inertial effects are negligible and the problem is thus reversible in time. The flow equations are solved with COM-SOL MULTIPHYSICS and verified by separate calculations with the ULAMBATOR code [23].

Results. – We first focus on the equilibrium position reached by the fiber far from the lateral walls, i.e. $\xi \to 0$. While for an I fiber all orientations are stable, i.e. the fiber keeps a constant orientation and translates without rotating, the L fiber reorients toward a stable orientation, and then drifts at a constant angle (Figs. 1(d,e)). We obtain numerically the evolution of the rotation speed $\hat{\theta}$ as a function of θ for an asymmetric L fiber with $\ell_a/h = 10$, $\ell_b/h = 5$, and $\beta = 0.76$ (Fig. 2(c)). There are two fix points separated by 180°: a stable one ($\theta = \theta_s$ close to -45°) and an unstable one ($\theta = \theta_u$ close to 135°). For all initial orientations, the fiber rotates monotonously until the stable orientation θ_s is reached. Note that close to the unstable orientation θ_u , a small variation can change the direction of rotation as depicted in Figs. 1 (d,e); although both fibers start at very similar configurations ($\theta \simeq 130^{\circ}$), the first fiber is rotating counter-clockwise while the second is rotating in the opposite direction until they both reach the stable angle ($\theta_s \simeq -50^\circ$). A fiber pushed out of the equilibrium orientation by an obstacle in the channel Fig. 2(d) rotates immediately back to the equilibrium position, showing the attractive strength of the stable fixed point. Close to the stable orientation, the rotation velocity $\hat{\theta}$ depends approximately linearly on θ (dashed line in Fig. 2(c), i.e. the angle increases/decreases exponentially in time to reach its stable value θ_s . We use this result to determine θ_s experimentally with an exponential fit (Fig. 2(d)), as detailed in the supplementary materials.

The stable orientation angle θ_s and the corresponding drift angle α_s are uniquely defined by fiber geometry and transversal confinement. Figure 3 shows both quantities as determined in the experiment for different lengths of the long arm ℓ_a/h , i.e. for varying asymmetry, and compared to the numerical results. While the drift angle varies only slightly in the examined regime, the stable orientation angle θ_s evolves non-monotonously with increasing length of the long arm ℓ_a/h : it first increases, reaches a maximum at $\ell_a/h \sim 7.5$, and then decreases again. A variation of the transversal confinement impacts both θ_s and α_s , as visualized by the gray shaded regions in Fig. 3. While the effect of β is almost negligible for $\beta < 0.6$, the orientation and drift angles increase rapidly with increasing confinement. In particular, we found that increasing the transversal confinement increases the rotation speed θ , i.e. the higher (lower) the transversal confinement, the faster (slower) the fiber approaches the stable orientation (see supplementary materials).

In order to obtain a general overview of the dependence of θ_s and α_s on the fiber geometry, we systematically compute these quantities in the parameter space $\{\ell_a/h, \ell_b/h\}$ and visualize the result in a map as shown in Fig. 4. For $\ell_a = \ell_b$ (black line in Fig. 4), the fiber is symmetric and is transported with $\theta_s = -45^\circ$ along the flow direction, i.e. $\alpha_s = 0^\circ$. For $\ell_a > \ell_b$ the L fiber is fully asymmetric as long as $\ell_b > h$, and the map of stable orientations θ_s can be divided into two distinct regions. For large values of the aspect ratios ℓ_a/h and ℓ_b/h , the isolines of constant θ_s approach straight lines i.e. θ_s depends on the asymmetry ratio ℓ_a/ℓ_b only and is independent of the fiber height hand thus the fiber aspect ratios. In this region, increasing asymmetry (ℓ_a/ℓ_b decreasing) leads to a decrease of θ_s , as evidenced by the white dots and the corresponding fiber



Fig. 3: Stable orientation angle θ_s (a) and corresponding stable drift angle α_s (b) as a function of the long arm aspect ratio ℓ_a/h , for $\ell_b/h = 5$. Black squares show experimental measurements, red circles correspond to numerical calculation with a transversal confinement of $\beta = 0.76$. The two grey shades correspond to $\beta = 0.76 \pm 0.08$ and $\beta = 0.76 \pm 0.16$ respectively.

shapes.

At small values of the aspect ratios (≤ 10), the isolines exhibit a different tendency: changing ℓ_a or ℓ_b while keeping ℓ_a/ℓ_b constant leads to different values of θ_s , i.e θ_s depends not only on the fiber asymmetry, but also on the fiber aspect ratios. Keeping for example ℓ_b/h constant and changing ℓ_a/h (red dots in Fig. 4), as we did in the experiments shown in Fig. 3, leads to a non-monotonous evolution of the orientation angle. The crossover between these two regimes can be evidenced by following the isoline for $\theta_s = -46^\circ$ (black dots and corresponding shapes). Along this line, the fiber shape first changes significantly at small fiber arm aspect ratios, but finally reaches an homothetically similar shape at large values of the aspect ratio.

For asymmetric fibers, which form an angle θ_s with the flow direction, there is a lateral drift whose magnitude depends on a combination of both equilibrium angle and asymmetry. For a fixed ℓ_b/h , changing ℓ_a/h (red dots) leads to a small change in drift angle although the orientation angle varies significantly. On the contrary, for a



Fig. 4: Isolines of constant stable orientation angle θ_s (bottom right corner) and constant stable drift angle α_s (top left corner) as a function of the fiber arm aspect ratios ℓ_a/h and ℓ_b/h . Both maps are symmetric around the black line defined by $\ell_a = \ell_b$, where $\theta_s = 45^\circ$ and $\alpha_s = 0$. Numerically inaccessible regions are shaded in gray.

given orientation (black dots), changing the shape leads to a significant change in drift angle. In the limit of large fiber arm aspect ratios, changing the asymmetry ℓ_a/ℓ_b (white dots) leads to significant variations in orientation and drift angle.

These findings demonstrate that it is not possible in general to rationalize the fiber transport using only the fiber asymmetry ℓ_a/ℓ_b , but that the two-dimensional geometry of the fiber has to be taken into account instead of a one-dimensional skeleton.

The overall fiber dynamics is given by a combination of rotation toward θ_s , drift, and interaction with the lateral walls. In order to obtain a more global view, we calculate the fiber trajectories in the configuration space spanned by θ and y for I, T and L fibers for a lateral confinement of $\xi = 0.5$, transversal confinement of $\beta = 0.76$ and a long arm aspect ratio $\ell_a/h = 10$ (left panel of Fig. 5). In the case of T and L fibers, the short arm has half the length of the long arm, i.e. $\ell_b/h = 5$. The trajectories obtained



Fig. 5: Trajectory map in the configuration space spanned by orientation angle θ and lateral position y for (a) an I fiber, (b) a T fiber, and (c) an L fiber. On the left side, numerical results are shown. The physical accessible space is shaded in color. For T fibers, the space of trajectories ending at the channel center is shaded in light green. The space of trajectories ending at the wall at y = 0.5 (resp. y = -0.5) is shaded in light blue (resp. light red). Stable and unstable fix points are highlighted in green and red, respectively. Long arm aspect ratio $\ell_a/h = 10$, lateral confinement $\xi = 0.5$ and transversal confinement $\beta = 0.76$ in all cases. The short arms of the T and L fibers have half the length of the long arm, i.e., $\ell_b/h = 5$. On the right side, experimentally obtained trajectories are shown. Some numerical and experimental trajectories are highlighted for comparison.

experimentally for various parameter sets are presented in the right panel of Fig. 5. While a direct comparison of theory and experiment is difficult due to different values of confinements and fiber arm aspect ratios ($0.7 \le \beta \le 0.8$, $0.12 \le \xi \le 0.8$, $10 \le \ell_a/h \le 20$), the qualitative trend, however, is clearly reproduced.

As already presented previously [10], I fibers show mostly permanent lateral oscillations, clockwise around the fix point at $\theta = 0^{\circ}$ (red trajectory, Fig. 1(a)) or anticlockwise around the fix point at $\theta = \pm 90^{\circ}$ (green trajectory, Fig. 1(b)) except if they are located very close to the wall (blue trajectory). If we reduce the level of symmetry by analyzing a T shaped fiber, the picture changes significantly. The stable fix points at the center of the channel for $\theta = 0^{\circ}, \pm 90^{\circ}, \pm 180^{\circ}$ are reduced to one at $\theta = 0^{\circ}$. Apart from trajectories ending at this configuration (red trajectory, Fig. 1(c)), there are also attracting points at the lateral channel walls (blue and green trajectories). While approaching these final positions, the T fiber may exhibit non-monotonous lateral movement as it is rotating. Moreover, the interaction with the lateral walls can lead to a change of rotation direction, as two of the four unstable fix points observed for I fibers are still present (highlighted by red dots in Fig. 5). For the fully asymmetric L fibers, the centrally located fix points finally disappear completely and the only permanent configurations correspond to the fiber being captured by one of the walls, with the sharp edge pointing toward the channel center. Even though there exist trajectories pointing away from this configuration, they finally lead back to it and the fiber cannot escape. The stable and unstable orientations observed without lateral confinement do not appear as fix points, as they lead to lateral drift, but as ridges with the trajectories either leading away from or attracting to. In other words, after rotating toward its stable orientation, the L fiber drifts toward the wall where it will remain stuck. In some cases (light red area), the fiber is captured by the opposite wall during the reorientation. We highlight the trajectories of the three cases presented in Fig. 1 (d-f). The fiber, initially close to the unstable orientation, leaves the orientation by rotating either clockwise (green curve, Fig. 1 (d)) or anti-clockwise (red curve, Fig. 1 (e)) to reach equilibrium. When approaching the wall with the sharp edge toward it (blue curve, Fig. 1 (f)), the fiber is first repelled, rotates until reaching its equilibrium angle, and finally drifts across the channel width to reach the top wall where it will remain. Note that for a mirrored fiber of opposite chirality, there exists a mirror-symmetric diagram where most fibers collect at the opposite wall.

For T and L fibers we can quantify the percentage of fibers being trapped at one of the channel walls or localized at the channel center. For T fibers, the corresponding set of initial configurations which end up in the channel center (light green) or at the walls (light red or blue) are highlighted in Fig. 5. Consequently, the areas of these regimes represent the statistical probability of finding a fiber with random initial orientation and lateral position at channel center or wall. In the presented case, approximately 40%of the fibers end in the channel middle and the rest are captured by the lateral walls. Looking at the trajectories ending at the walls, we can see that they correspond to the case where the fiber is captured by the wall during reorientation toward the central position. This means that we can tune this ratio by varying the lateral confinement ξ . In fact, for $\xi = 0.3$, we find approximately 73 % of the fibers in the channel center. Decreasing the lateral confinement thus increases the probability of finding a T fiber in the middle of the channel. It has to be noted, however, that close to the end points at the walls, there exist trajectories which lead away again from the wall. Assuming some experimental noise, this can easily lead to a higher amount of fibers finally ending in the channel center than obtained from a noise-free theoretical study. Turning to L fibers, most of them end at the same lateral wall (approximately 86% for $\xi = 0.5$, light blue area), which is determined by the sign of drift angle at stable orientation of a fiber without lateral confinement. Analogue to the T fiber, the partition of fibers being captured by the opposite wall can be reduced (increased) by decreasing (increasing) the lateral confinement (approx. 93% fibers at one wall for $\xi = 0.3$). See supplementary materials for details.

These findings show that it is possible to control the lateral position of fibers transported in confining microchannels by tuning their geometry, in particular their symmetry properties, and/or the confinement, i.e. the channel size. I fibers (two axes of symmetry) are mostly laterally oscillating, or tend to end in the channel center due to small imperfections (damped oscillation) [10]. T fibers (left/right symmetry, fore/aft asymmetry) are either pushed toward the channel center or toward the lateral walls, depending on the level of lateral confinement. L fibers (fully asymmetric) are always captured by the lateral walls. Depending on their chirality being left- or righthanded, most of the fibers end hereby at one or the other wall. In addition, the collection of fibers at the wall or at the middle of the channel strongly depends on drift velocity and drift angle, which represent the distance traveled to reach the wall, and reorientation dynamics, i.e. rotation speed and accompanying lateral movement, which all can be tuned by adjusting the transversal confinement. The presented results thus open new routes toward the design of sorting devices or filters as a function of for example micro-organism shape. In addition they can be used to design targeted delivery or particle capture applications in microfluidic devices.

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Appendix. -

Dynamics of orientation in an infinite medium ($\xi = 0$). Figure 6 (a) shows the evolution of the dimensionless rotation velocity $\dot{\theta} \, \ell_a / U_0$ as a function of the orientation angle θ for different transversal confinements. The amplitude of $\dot{\theta}$ increases for increasing confinement, i.e., the reorientation of the fiber towards its equilibrium orientation is faster when transversal confinement increases. For orientation angles close to the stable orientation angle θ_s , the evolution of $\dot{\theta}$ as a function of θ can be approximated by a linear function. The shaded region of Figure 6 (a) indicates this linear regime ($|\theta - \theta_s| < 30^\circ$), where the evolution of the orientation angle as a function of time is consequently expected to be exponential.

Figure 6 (b) shows the evolution of θ as a function of the dimensionless time tU_0/ℓ_a for three different confinements in the vicinity of the stable orientation angle θ_s as obtained from calculations with the ULAMBATOR code. After some time, the orientation angle reaches a plateau, which corresponds to the equilibrium orientation θ_s . For increasing transversal confinement θ_s increases and the equilibrium orientation is reached faster, which can be explained by the higher rotation velocity as shown in Fig. 6 (a).

The time evolution of the orientation angle can be fitted by an exponential saturation function:

$$\theta(tU_0/h) = (\theta_s - \theta_0) \left(1 - \exp\left(-\frac{tU_0}{\ell_a \tilde{\tau}}\right) \right) + \theta_0, \quad (1)$$

with $\tilde{\tau}$, and θ_s being the two fitting parameters, and initial orientation θ_0 .

Figure 6 (b) shows the fit (black curve) of the orientation angle evolution for the lowest confinement. Another example of such a fit is given in Figure 2 (d) of the article. The characteristic dimensionless time $\tilde{\tau}$ characterizes the dynamics of the particle orientation and depends on the fiber lenghts ℓ_a/h , ℓ_b/h and on the transversal confinement. These dependences are shown in Figure 7, where $\ell_b = 5h$ in order to stay consistent with the experiment. For both increasing confinement and increasing $\ell_a \tilde{\tau}$ increases as well.

Experimental measure of the equilibrium angle $(\xi = 0)$. Experimentally, the steady orientation angle of a L fiber evolving in an infinitely wide channel $(\xi = 0)$ is determined using intermediate numerical results. The measuring protocol is described in the following. For short fibers $(\ell_a/h < 12.5 \text{ and } \ell_b/h = 5)$ the influence of the lateral walls is negligible and the transient evolution of the orientation angle exhibits as expected an exponential evolution toward a plateau. Figure 8 shows the superposition of the this evolution as obtained experimentally (yellow curve) and in the simulation (red dots), as well as the exponential fit (black curve). The three curves show very good agreement validating both the numerical results and the pertinence of the exponential fit.



Fig. 6: Dynamics of orientation of an L fiber with $\ell_a/h = 10$ and $\ell_b/h = 5$ for different confinements $\beta = 0.6$ (yellow), $\beta = 0.76$ (orange) and $\beta = 0.9$ (red), as obtained from numerical calculations. (a) Evolution of the dimensionless rotation velocity $\dot{\theta}\ell_a/U_0$ as a function of the angle θ far away from the lateral walls. In the vicinity of the stable orientation angle θ_s , $\dot{\theta}$ depends approximately linearly on θ . (b) Evolution of the orientation angle as a function of the dimensionless time. The black curve corresponds to an exponential fit of the data using Eq. (1). From the fit one can determine the dimensionless characteristic time of the orientation process $\tilde{\tau}$.



Fig. 7: Dimensionless characteristic time as a function of ℓ_a/h for transversal confinements varying from 0.6 to 0.9. In all cases $\ell_b = 5h$.



Fig. 8: Evolution of the orientation angle as a function of the dimensionless time for an L fiber with $\ell_a/h = 7.5$, $\ell_b/h = 5$, and $\beta = 0.76$. A very good agreement is obtained between experiments (yellow), simulations (red), and the exponential fit (black).

For larger fibers, the orientation angle never reaches a plateau, which makes a direct measurement of the equilibrium angle impossible. Moreover, the fiber reorients with a longer characteristic time as compared to shorter fibers and drifts toward a lateral wall which impact the fiber trajectory and the orientation angle evolution. However, knowing the dimensionless characteristic time $\tilde{\tau}$ one can extrapolate the experimental observation of the orientation angle evolution. To distinguish the dynamics caused solely by to the particle shape and the external flow from those caused by an interaction with the wall, we fit a portion of the transient evolution of θ , corresponding to the situation where the fibers is far from the walls, by the exponential function (1). We keep θ_s as a fitting parameter but set the value of $\tilde{\tau}$ to the one obtained numerically. This one-parameter fitting method allows us to extract the steady orientation angle from the experiments. Note that this procedure is based on the good agreement between numerical results and experiments (see Fig. 8) not only with respect to the equilibrium angle, but also regarding the transient evolution, i.e., the characteristic time of reorientation $\tilde{\tau}$.

Effect of lateral confinement on the fiber distribution in We calculate the trajectories of T and L the channel. fibers for at least 10^4 initial configurations equally distributed in the configuration space. Figure 9(a) shows the distribution in lateral position for a lateral confinement of $\xi = 0.5$. We then analyze the distribution after transportation in a channel of length $L = 10^3 \ell_a$. As shown by Fig. 9(b), T fiber are either collected in the channel center $(\sim 41\%)$ or at both lateral walls ($\sim 59\%$), while most of the L fibers accumulate at one of the lateral walls (86%). This effect can be tuned by changing the lateral confinement, as visualized by Fig. 9(c) for $\xi = 0.3$. In this case, more T fibers are at the channel center ($\sim 73\%$) and the percentage of L fibers being located at the same lateral wall is increased.



Fig. 9: Distribution of lateral position in the channel for T (top) and L (bottom) fibers: Initial distribution for $\xi = 0.5$ (a), and distribution after $L = 10^3 \ell_a$ for (b) $\xi = 0.5$ and (c) $\xi = 0.3$.

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016