MIGRATION OF FLEXIBLE FIBERS ENTRAINED BY POISEUILLE FLOW IN A MICROCHANNEL

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Summary In this work, we consider a single non-Brownian mobile and flexible fiber immersed in Poiseuille flow in a channel consisting of two parallel infinite walls. The dynamics of the fiber is evaluated numerically from the Stokes equations by a multipole code HYDROMULTIPOLE. Investigating the fiber dynamics we found out that fibers migrate to a critical position across the channel. The distance between the wall and a limiting position depends on the fiber elongation and flexibility. For more stiff fibers the critical position results from the interplay between their tendency to drift away from the channel and the repulsive hydrodynamic interaction with the wall. For less stiff fibers the limiting position is not influenced by the presence of the wall. Differences between the critical position for different fibers can be used in the process of microfibers separation by the flow.

INTRODUCTION

Migration of fibers in Poiseuille flow [1, 2, 3, 4, 5] is the fundamental problem of modern lab-on-chip hydrodynamics, important in various biological, medical and industrial contexts. Dynamics of flexible fibers in simple shear and Poiseuille flows has been analyzed theoretically, numerically and experimentally in numerous publications [6, 7, 8, 9, 10, 11, 12, 13]. In our previous papers [14, 15] we investigated dynamics of fibers in Poiseuille flow. In particular, in Ref. [15] we found out that the migration rate towards the central plane of the channel can be increased by a suitable choice of the fiber stiffness, aspect ratio and distance from the wall. But for certain values of these parameters, fibers migrate away from the central plane. As we showed in [16], the migration process is characterized by a critical distance z_c from the wall where fibers tend to accumulate. In this paper we describe in details how the accumulation points z_c depend on stiffness and aspect ratios of fibers.

SYSTEM AND METHOD

We study motion and shape deformation of a single non-Brownian flexible fiber in Poiseuille flow with negligible inertia. The fluid is bounded by two planar solid walls at $z = 0$ and $z = h$, with the Poiseuille flow velocity $\mathbf{v}_0 = 4v_m z(h - z)/h^2\, \hat{\mathbf{x}}$. The stick boundary conditions are satisfied at the surface of the fiber and at the solid walls, which confine the fluid. At infinity, the fluid velocity $\mathbf{v} = \mathbf{v}_0$. To characterize a single fiber the bead model is used [17]. A fiber strand is constructed out of N solid spherical particles of diameter d which can move with respect to each other. The relative motion of the beads results from elastic and bending forces. The stretching parameter k of Hook's law of a fiber is large and fixed. We change the bending stiffness of a fiber which is measured as the ratio A of the bending force to a force related to the ambient Poiseuille flow of a given amplitude v_m. The straight configuration is the equilibrium configuration of the fiber. Initially the fiber is straight and placed along the flow with distances between the bead surfaces very small with respect to d. Therefore the motion of the fiber takes place in a single plane. The dynamics of the fiber is calculated by the multipole method of solving the Stokes equations [18], implemented in the numerical code HYDROMULTIPOLE [19]. From now on distances will be normalized by the fiber thickness d, velocities by the maximal velocity v_m of the Poiseuille flow, forces by $f_0 = \pi\eta d v_m$, and time by $t_0 = d/v_m$.

RESULTS

Dynamics of fibers has been evaluated for initial configurations with different initial distances from the wall z_0 and different values of the fiber elongation N and stiffness A. We have considered fibers with $N = 5, 10$ and 20 beads, shorter than the channel width $h = 50$, for several value of the stiffness parameter A in the range $0.025 \leq A \leq 2$. Fig. 1 shows evolution of a fiber center-of-mass $z_m(t)$, starting from different values z_0, for fiber elongation $N = 5$ and 10, and the stiffness parameter $A = 0.025, 0.2$ and 1. Positions of the fibers, which move towards (away from) the central plane of the channel are plotted in red (blue). Each fiber migrates towards a certain critical distance from the wall z_c. The value of z_c is a function of the stiffness A and the elongation N, as shown in the caption of Fig. 1.

We have found out that for a large stiffness, shorter fibers (with $N = 5$) accumulate at a critical position z_c much closer to the wall than the longer ones (with $N = 10$), only a bit smaller than the fiber length, $z_c \lesssim N$. However, z_c significantly increases and exceeds N when A becomes sufficiently small. For short and stiff fibers ($N = 5, A = 0.2, 1$) the critical position is equal to $z_c = 4.3 \pm 0.1$ (Fig. 1 a,b), but for more flexible fibers ($A = 0.025$), it becomes much (more than three times) larger, $z_c = 16.81 \pm 0.05$ (Fig. 1 c). The same tendency is observed for longer fibers with $N = 10$. For more stiff fibers ($N = 10, A = 1$), the critical distance $z_c = 7.5 \pm 0.1$ (Fig. 1 d); but more flexible ($A = 0.2$) fibers accumulate at a much larger critical distance from the wall, $z_c = 15.9 \pm 0.1$ (Fig. 1 e). It seems that accumulation of stiff fibers is

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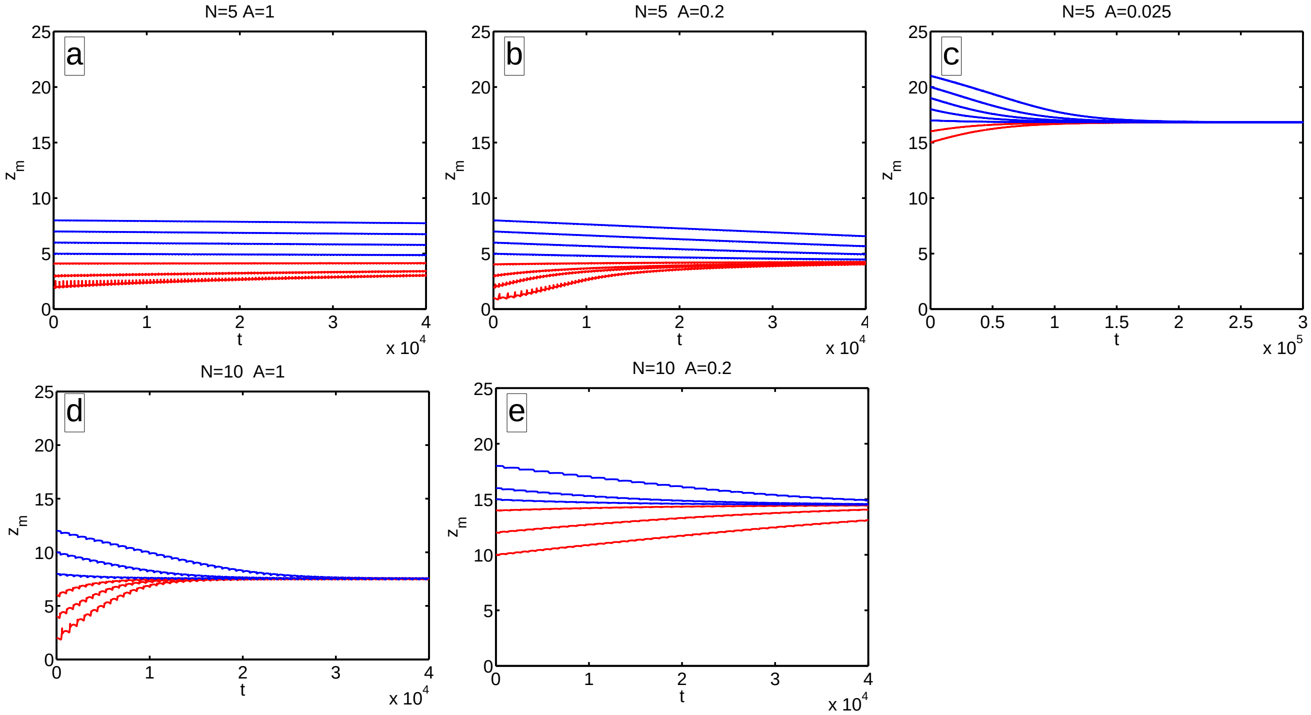

Figure 1. Evolution of a fiber center-of-mass z_m, starting from different positions $z_m(0) = z_0$, and for different values of fiber elongation N and stiffness A. Here, $z = 0$ and $z = 25$ correspond to the wall and the central plane of the channel, respectively. Fiber centers of mass tend to reach a critical distance z_c from the wall, with $z_c = 4.3,\ 4.3,\ 16.81,\ 7.5,\ 14.45$ for the panels a, b, c, d, e, respectively.

caused by the wall, which prevents them from escaping. Flexible fibers accumulate owing to their shape deformation and the flow curvature, independently of the wall. This explanation is confirmed by simulations performed in the same system but without walls. For more flexible fibers, z_c is practically the same both with and without the walls. However, more stiff fibers in the absence of walls migrate out of the channel, whatever is their initial position across the flow; there is no accumulation points, in contrast to the system with the walls.

CONCLUSIONS

We have proposed a method to separate non-Brownian flexible microfibers, depending on their length and bending stiffness. Our key finding is that fibers with different lengths and different ratios A of the bending stiffness to the flow amplitude, tend to accumulate at significantly different critical distances z_c from the wall.

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