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Preface

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MIGRATION OF VESICLES AND FLEXIBLE FIBERS IN POISEUILLE FLOW

Alexander Farutin^{*1,2}, Tomasz Piasecki^{†3}, Agnieszka M. Słowicka³, Chaouqi Misbah^{1,2}, Eligiusz Wajnryb³, and Maria L. Ekiel-Jezewska^{‡3}

¹*Univ. Grenoble Alpes, LIPHY, F-38000 Grenoble, France*

²*CNRS, LIPHY, F-38000 Grenoble, France*

³*Institute of Fundamental Technological Research, Polish Academy of Sciences, Pawińskiego 5B, 02-106 Warsaw, Poland*

Summary Dynamics of flexible fibers and vesicles in unbounded planar Poiseuille flow at the low-Reynolds-number are shown to exhibit similar basic features, when their equilibrium (moderate) aspect ratio is the same and vesicle viscosity contrast is relatively high. The lateral migration and accumulation of these two types of flexible objects are analyzed numerically.

In this paper, we investigate whether different flexible objects – vesicles and flexible fibers made of beads – may share similar features, or even some universal behaviors, regarding their migration properties. Revealing similarities between apparently different systems would advance our understanding of the migration mechanism and allow for using simpler models, which are numerically more efficient.

A single flexible object is entrained by an unbounded Poiseuille flow with velocity $v_\infty = (\alpha y^2 - v_m) e_x$, where α is the flow curvature. The value $-v_m$ of the flow velocity at the central plane $y=0$ is irrelevant for the migration or shape evolution. The dynamics of the flexible object is derived from the Stokes equations, using the boundary integral method for vesicles [1, 2, 3] and the multipole expansion (implemented in the HYDROMULTIPOLE numerical codes) for the fiber beads [4, 5].

A vesicle has a constant area S and a constant volume V , and its geometry is described by the radius of the sphere having the same volume, $R_0 = (3V/4\pi)^{1/3}$, and the reduced volume $\nu = 6\sqrt{\pi}VS^{-3/2}$. The other parameters which determine the vesicle deformation and motion under flow are the ratio λ of the fluid viscosities inside and outside, and the dimensionless capillary number $C_a = \alpha R_0^4 \eta / \kappa$, defined as the dimensionless ratio of the hydrodynamic to bending forces (the first one proportional to the flow curvature α and fluid viscosity η , and the second one – to the vesicle bending modulus κ).

Flexible fiber is modeled as a chain of N identical spherical solid beads of diameter d . Following Refs. [4, 5, 6, 7, 8], we impose the constraint elastic and bending forces which act on each bead, in such a way that the total external force and torque on the fiber vanish. The bead centers are connected by springs with the equilibrium length $l_0 d$ only slightly larger than the bead diameter d , with $l_0 = 1.01$, and the Hooke's spring constant \tilde{k} . As in Ref. [5], the ratio of the elastic to viscous forces is given in terms of the dimensionless parameter $k = \tilde{k}/(\pi\eta v_m)$. We set $k = 80 \gg 1$. With this choice, the fiber practically does not change its length during the motion, and the specific value of k is irrelevant. The relevant quantity is the ratio of bending and viscous forces, $A = \tilde{A}(625\pi\eta d^5 \alpha)^{-1}$, where \tilde{A} denotes the fiber bending stiffness. [5]

To match flexible fibers with vesicles, we focus on vesicles with relatively large viscosity contrast, $\lambda = 12$. Moreover, we choose relatively low aspect ratio – our fiber is made of $N = 5$ beads. We circumscribe the fiber at the equilibrium position by the spherocylinder, and match its volume and surface with the corresponding volume and surface of the vesicle at the equilibrium, what results in the choice of $\nu = 0.6$. The goal is to analyze how the dynamics of flexible objects depends on their dimensionless bending stiffness, i.e. A for fibers and C_a^{-1} for vesicles.

Each of our flexible objects is initially aligned with the flow. While translating with the flow, it tumbles and changes shape. The basic task, however, is to determine the motion of the center of the flexible object across the flow. For vesicles, the center is determined as the center of mass of the membrane. For fibers, we take their center of mass, with the position calculated as the arithmetic mean of the positions of all the bead centers. The center keeps the same z -coordinate, but its y -coordinate (denoted here as y_0) changes slowly with time. Examples of the time evolution of the dimensionless position y_0/R_0 of the center are shown in Fig. 1, with the use of $(\alpha R_0)^{-1}$ as the time unit. It is clear that both vesicles and flexible fibers migrate across the flow and their centers tend to a certain accumulation plane, $y_0 \rightarrow y_c$. The position y_c depends on the bending stiffness. In Fig. 1, we have matched the values of $C_a = 0.08$ and $A = 0.024$ in such a way that both vesicles and fibers accumulate at the same distance $y_0/R_0 \approx 8.2$ from the central plane.

The dynamics of a flexible object, which is relatively far from the central plane of the flow, satisfy a universal scaling [5, 9] – the fiber essential dynamics, including its deformation and migration, is determined only by the local shear rate $2\alpha y_0$. As the result, the accumulation position y_c is a linear function of the bending stiffness, as shown in Fig. 2. The same accumulation positions correspond to the bending stiffness of vesicles and fibers related to each other by the expression $1/C_a \approx 520A$.

*A. Farutin, T. Piasecki and A. M. Słowicka contributed equally to this work.

[†]Present address: Institute of Mathematics of the Polish Academy of Sciences, Śniadeckich 8, 00-656 Warsaw, Poland

[‡]Corresponding author. Email: mekiel@ippt.pan.pl

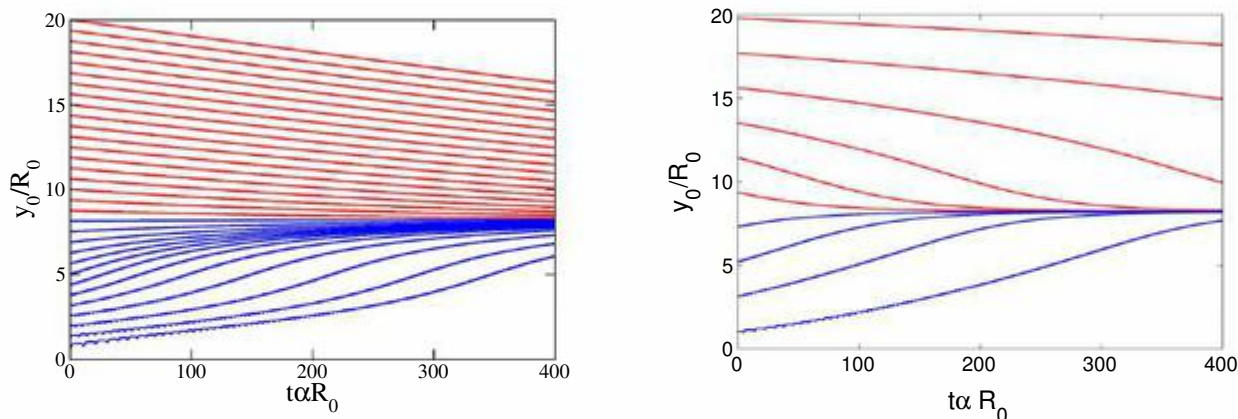


Figure 1: The time-dependent distance y_0/R_0 from the center of flexible object to the central plane of the flow. Vesicles with $C_a = 0.08$ (left) and fibers with $A = 0.024$ (right) accumulate at the same distance $y_c/R_0 \approx 8.2$. The blue and red lines indicate migration outward and inward, respectively.

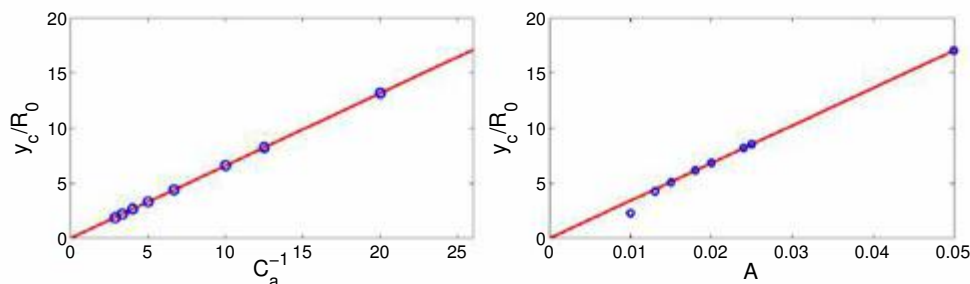


Figure 2: The accumulation position y_c/R_0 of vesicle (left) and fiber (right) vs. its bending stiffness.

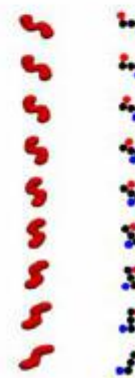


Figure 3: Evolution of shapes. $C_a = 0.15$, $y_0/R_0 = 9.3$.

In the following part of the paper, we analyze how other features of the dynamics of single vesicles and fibers depend on their bending stiffness. We evaluate the tumbling frequency and the migration velocity across the flow, study evolution of shape, compare the universal scaling based on the local shear with the dynamics in the pure shear flow. We also present examples of the motion and deformation of more elongated flexible objects, and demonstrate that the second (coiled) mode of the dynamics exists not only for fibers [8] but also for vesicles. We observe that fibers can migrate slower or faster than vesicles of the matched flexibility, depending on the range of the parameters. However, the overall similarity of the corresponding shapes (see Fig. 3) is evident, what allows to suppose that the accumulation mechanism of vesicles and fibers is essentially the same.

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