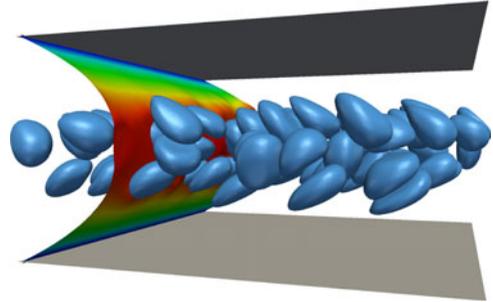# Soft suspensions: inertia cooperates with flexibility

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Cross-streamline migration of soft particles in suspensions is essential for cell and DNA sorting, blood flow, polymer processing and so on. Pioneering work by Poiseuille on blood flow *in vivo* revealed an erythrocyte-free layer close to blood vessel walls. The formation of this layer is related to a viscous lift force caused by cell deformation that pushes cells towards the centre of blood capillaries. This lift force has in this case a strong impact on blood flow. In contrast, rigid spherical particles migrate from the centre towards the periphery, owing to inertia (the Segré–Silberberg effect). An important open issue is to elucidate the interplay between particle deformation and inertia. By using a capsule suspension model, Krueger, Kaoui & Harting (*J. Fluid Mech.*, 2014, vol. 751, pp. 725–745) discovered that capsule flexibility can suppress the Segré–Silberberg effect and inertia promotes overall flow efficiency thanks to a strong inertial flow focusing effect.

Key words: particle/fluid flows, rheology, suspensions

1. Introduction

Nearly two centuries have passed since the French physician Poiseuille (1830) reported that in the microvasculature there exists a cell-free layer near blood vessel walls, a layer of plasma devoid of red blood cells (RBCs). One century later Fahraeus & Lindqvist (1931) showed that this cell-free layer has a strong and counter-intuitive impact on rheology: the more blood is confined, the better it flows. The existence of a cell-free layer dramatically reduces blood flow dissipation in the organism. The cell-free layer is caused by RBC migration from vessel walls towards the centre. At the scale of RBCs (few micrometres), the Reynolds number encountered *in vivo* is small. When inertia is small, a rigid spherical particle cannot undergo cross-streamline migration, owing to the reversibility of the Stokes equations upon time reversal. However, soft particles, like RBCs, deform in response to a flow causing an asymmetry in the shape between the upstream and downstream sides of

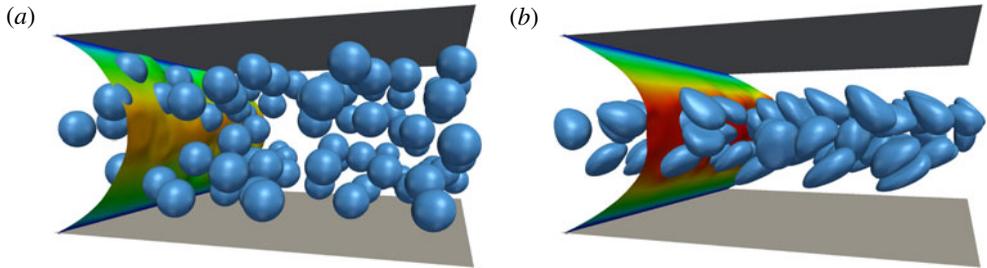† Email address for correspondence: chaouqi.misbah@ujf-grenoble.fr

FIGURE 1. Configuration of suspension under Poiseuille flow: (*a*) weakly flexible particles at $Re = 50$ and Segré–Silberberg effect; (*b*) amply flexible particles at $Re = 417$, revealing a strong inertial focusing with two wide bands of particle-free layers. Instantaneous velocity profiles are shown in both figures (red, high velocity; blue, low velocity).

the particle that destroys the overall time reversal symmetry (when fluid equations are associated with boundary conditions on a flexible surface). This results in a lift force towards the centre of the channel, and has been analysed in numerical simulations and *in vitro* experiments (Coupier *et al.* 2008; Kaoui *et al.* 2008). (See figure 1.)

Inertia is another, perhaps more familiar, source of lift force, responsible for aircraft flight, or curved trajectories of a spinning ball. Segré & Siberberg (1961) reported that, in a tube under Poiseuille flow, a dilute suspension of rigid spheres self-organizes into an annulus around the tube centre. The central position is unstable, and particles migrate, thanks to inertia, towards a concentric annular region with a mean radius of approximately 0.6 of the tube radius. Migration caused by inertia (with no deformation) pushes the particle away from the centre, while particle deformation (with no inertia) favours migration towards the centre of the channel.

The *in vivo* Reynolds number of RBCs is generally small. However, in several lab-on-chip technologies, where this study can find applications, very fast processing may be required involving large velocities so that inertia can be significant. An important health-care example is the exploitation of the lift force in separating and sorting out cancer cells from healthy blood cells (Hur *et al.* 2011; Tanaka *et al.* 2012). Despite its fundamental and obvious technological importance, the issue of how the interplay between these two phenomena could alter the general picture of cross-streamline migration, and what are far-reaching consequences, had remained open until now. The work of Krueger, Kaoui & Harting (2014) has filled this gap.

2. Overview

Krueger *et al.* (2014) considered a suspension of capsules in a plane Poiseuille flow between two parallel plates. Capsules are usually obtained thanks to interfacial polymerization of a liquid drop (natural or synthetic polymers such as poly(L-lysine), alginate or polyacrylates) with nonlinear mechanical properties. Capsules are the focus of many biological applications, the most prominent being the field of specific drug delivery carriers. Capsule membranes are endowed with shear elasticity (Barthès-Biesel 2009), mimicking the cytoskeleton of the RBCs (a cross-linked network of protein anchored in the RBC phospholipid bilayer membrane). The capsule surface area is more or less extensible under external forces. Krueger *et al.* (2014) modelled the capsule as a two-dimensional geometrical surface with an in-plane membrane shear and bending elasticity. The Helfrich (1973) and Skalak *et al.* (1973) models are adopted for shear elasticity and bending modes, respectively. The capsule is immersed in a fluid and acts on it via both shear and bending forces.

The authors first address the Segré–Silberberg effect by considering quite rigid capsules, and confirm that particles are pushed away from the flow centreline. However, when allowance is made for enough particle flexibility, the Segré–Silberberg effect can be suppressed, or even its tendency can be reversed. Indeed, they find that inertia acting on flexible particles can strongly enhance migration towards the centre, in comparison to the effect already documented in the pure Stokes regime. The 'soft' Segré–Silberberg effect (inertia effect on soft particles) acts in the same direction as the viscous lift force; inertia helps flexible particles to move towards the centre. This result is essential in the field of soft suspensions and reveals quite interesting features regarding rheological properties of capsule suspensions. One of the most prominent findings of this study is that, beyond a critical capsule Reynolds number (of approximately 40), the apparent viscosity of suspension decreases as a function of an appropriate Reynolds number Re. This decrease in viscosity is concomitant with an ample increase of the cell depletion layer.

For small enough Re the depletion layer is almost constant or exhibits only a weak decrease. Owing to the weak decrease of the cell-free layer, the flow efficiency is also only weakly reduced (the apparent viscosity increases slowly). At a critical value of Re the depletion layer shows two distinct tendencies depending on particle flexibility: (i) it continues to decrease if the capsules are rigid enough, or (ii) it exhibits a sudden increase if the capsules are soft enough. More precisely, for rigid enough particles, the Segré-Silberberg effect dominates and particles are expelled towards the periphery, resulting in lower flow efficiency (increase of apparent viscosity). Conversely, when particles are soft enough, the Segré–Silberberg effect is not only suppressed, but rather acts in the opposite direction as compared to its effect on rigid particles: particles are further focalized towards the centre of the channel in comparison to the case where inertia is absent. This inertial focusing acts in the same direction as the viscous lift force caused by particle flexibility. Hence the cooperative effect of both inertia and particle flexibility results in a dramatic jet focusing, which entails a significant decrease of apparent viscosity. The study of Krueger *et al.* (2014) reveals a bifurcation point as a function of Re, which marks a transition between a regime where inertia reduces flow efficiency, and that where it promotes it. This change of behaviour occurs only if particles are flexible enough, revealing a critical flexibility parameter (denoted Ca in the paper by Krueger *et al.* (2014)) required for this change of regime. For rigid enough capsules, inertia always enhances viscosity.

In order to interpret this remarkable property, Krueger *et al.* (2014) introduce the notion of local viscosity in the channel, which is defined as

$$\eta_{loc} = \frac{1}{\eta_0} \frac{\sigma(z)}{\dot{\gamma}(z)}, \tag{2.1}$$

where η_0 is the solvent viscosity, and $\sigma(z)$ and $\dot{\gamma}(z)$ are the local stress and shear rate measured within a small layer of the suspensions that is parallel to the flow direction. Across the channel the capsule volume fraction ϕ varies (it is high in the centre and low at the periphery), thus allowing one to study the local viscosity as a function of the local volume fraction $\phi(z)$. Local viscosity η_{loc} increases (linearly) with ϕ, as expected. For any explored volume fraction ϕ, η_{loc} is always found to increase with Re. This effect is attributed to the increase of capsule inclination angle due to inertia (in agreement with the work of Laadhari, Saramito & Misbah (2012)): the particles assume a larger cross-section in the channel, which in turn leads to a larger flow resistance, resulting in a higher local viscosity. This led to two conclusions.

(i) The increase of η_{loc} with *Re* (resulting from increase of capsule inclination angle) contributes to an increase in apparent viscosity with *Re*. (ii) In turn, inertial focusing of suspension leaves large bands of cell-free layers close to the walls where the shear rates are the highest, and this should contribute to an opposite: reduction of the apparent viscosity. The interplay between these two effects dictates the peculiar behaviour of the apparent viscosity with *Re* for different degrees of flexibility, as shown in figure 2 of Krueger *et al.* (2014). For soft enough particles effect (i) is overcompensated by effect (ii), leading to a decrease of apparent viscosity with *Re*.

3. Future

Krueger *et al.* (2014) provide a novel and major input regarding the impact of inertia on the spatiotemporal organization of suspended soft entities and their link with overall macroscopic rheology. One natural extension is the study of polydisperse suspensions in order to identify the mechanisms of segregation processes with the aim to apply the idea to lab-on-chip technologies, such as cell sorting, diagnosis, etc. Another possible extension would be to explore the effect of pulsatile flows on the suspension spatiotemporal organization. Local oscillations in shear rates combined with a local flexibility parameter due to a polydisperse character of the suspension (e.g. healthy and pathological cells) should offer a new and tunable tool to efficiently guide the emergence of new patterns of the suspended entities. This should open the way to novel rheological properties and intelligent control of soft suspensions in more complex flow architectures.

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