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DYNAMICS OF ARTIFICIAL CAPSULES AND ERYTHROCYTES

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ABSTRACT

The study of the interfacial dynamics of artificial or physiological capsules (i.e. membrane-enclosed fluid volumes) in Stokes flow has seen an increased interest during the last few decades due to their numerous engineering and biomedical applications. Artificial capsules are commonly used in the pharmaceutical, food and cosmetic industries for the controlled release of medical agents, aromas or flavors. In addition, the motion of red blood cells through vascular microvessels has long been recognized as a fundamental problem in physiology and biomechanics, since the main function of these cells, to exchange oxygen and carbon dioxide with the tissues, occurs in capillaries [1].

Current understanding of capsule dynamics at high flow rates is rather limited. Existing analytical and computational studies are unable to predict (and thus provide physical insight on) the elongated capsule shapes at high flow rates. In particular, the asymptotic solutions for initially spherical capsules are restricted to small deformations while the state of the art (low-order) three-dimensional computational methodologies fail to determine large membrane deformations.

To contribute to the physical understanding in this area, we utilize our (high-order) interfacial spectral boundary element algorithm for capsules with elastic tensions to study large deformations, in a planar extensional Stokes flow, of a capsule made from a strain-hardening membrane. Our membrane description is based on the well-established continuum approach and the theory of thin shells. Typical membrane thickness ranges from $O(\mu m)$ for alginate capsules, to $O(nm)$ for synthetic polysiloxane capsules (i.e. it is several orders of magnitude smaller than the size of the capsule), and thus the thin-shell theory has proven to be an excellent description of these membranes. To describe a strain-hardening membrane we use the Skalak constitutive law which accounts for both shearing and area-dilation, and while originally developed to describe biological membranes (such that of the erythrocyte), it can also be employed to model membranes obtained by interfacial polymerization [1,2]. It is of interest to note that our interfacial algorithm, owing to its spectral nature, determines accurately all interfacial properties (including curvature and membrane tensions), as our earlier studies have revealed [3,4].

Our computational study shows that a (strain-hardening) Skalak-type capsule in a planar extensional Stokes flow develops steady-state shapes whose edges from spindled become cusped with increasing

flow rate owing to a transition of the edge tensions from tensile to compressive. A bifurcation in the steady-state shapes is also found (i.e. existence of both spindled and cusped edges for a range of high flow rates) by implementing different transient processes. The linear increase of the maximum steady-state tension with the flow rate can be used to predict membrane rupture.

As the flow rate increases, the transition from spindled to cusped shapes allows the capsule to withstand the increased hydrodynamic forces, as found for low-viscosity drops or bubbles in strong extensional Stokes flows [5]. We note that strong flows are commonly encountered in industrial and physiological processes including the microcirculation. Our study also shows that no critical flow rate exists for strain-hardening membranes in extensional flows, i.e. for any flow rate the capsule reaches a steady-state (assuming that the tensions on the membrane are smaller than its lytic tension). The shape transition is possible via the appearance of compressive tensions near the capsule edges at high flow rates. Thus, the importance of compressive tensions should be recognized either as a result of mechanical deformation (as in our work) or owing to a (bio)physical process (as in the case of a fluid vesicle undergoing lipid uptake [6]).

We also consider the dynamics of red blood cells (or erythrocytes) in strong shear flows. Our computational results for the cell deformation are in excellent agreement with experimental findings from ektacytometry. We note that in strong flows the relationship between flow rate and cell deformation is logarithmic; such behavior is not observed for droplets or for spherical capsules. To the best of our knowledge, no previous numerical methodology has been able to reproduce accurately real ektacytometry data at high flow rates. In addition, our interfacial spectral boundary algorithm allows analysis of the erythrocyte dynamics beyond the capabilities of ektacytometry and other experimental techniques. For example, our work provides further insight on the transition of the erythrocyte motion from tank-treading to tumbling.

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