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The role of fluid-structure interactions in artificial capsule mechanics

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ABSTRACT

A simple capsule consists of an internal medium (pure or complex liquid) enclosed by a deformable membrane. Such artificial capsules are used for protection and/or controlled release of the internal medium (drug delivery systems, cosmetics, food industry, etc.). Their size ranges from a few microns to a few millimetres, and their membrane deformability depends on thickness and the material used. When a liquid filled capsule is suspended into another flowing liquid, it is deformed by viscous fluid stresses and may sometimes burst. The particle Reynolds number is small, so that the capsule motion involves inertialess interactions between the viscous flow of two liquids and the large deformation of a thin membrane. The determination of a capsule motion and deformation thus involves the solution of a fluid-structure interaction problem which is very complicated in general. However, understanding this process is crucial for artificial capsule design, assessment of the membrane mechanical properties and break-up control.

A simple situation corresponds to the case where the internal and suspending liquids are both Newtonian, and where the membrane is very thin, hyper-elastic and devoid of bending resistance. Correspondingly, the motions of the internal and external liquids are described by the Stokes equations, whereas the capsule wall is treated as an elastic surface. It is possible to use the boundary integral formulation of the Stokes equations that avoids solving for the fluid motion in the whole flow domain. The capsule wall is tessellated with an unstructured or structured mesh. The use of the later allows easy interpolation of the different quantities of interest along the surface and thus reduces the number of node points. The node positions are obtained at each time step by means of Lagrangian tracking.

Different situations with increasing complexity can be considered depending on the capsule physical properties (geometry, membrane behaviour) and the flow. Here we concentrate on the case of initially spherical capsules. The simplest situation corresponds to a single capsule freely suspended in a simple shear flow [1,2]. It is found that the capsule behavior depends on shear rate (fig. 1): for low shears, it is unstable and shows a tendency towards folding; for high shears, pointed tips are observed and burst is conjectured to occur; for medium shears, it is stable and the membrane tank-treads around the steady

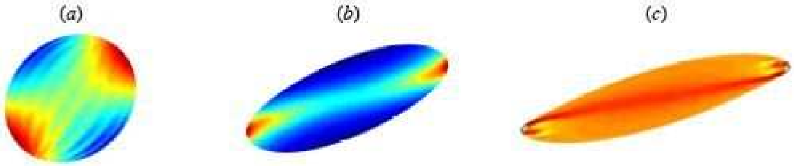

Figure 1: Capsule in simple shear flow for (a) low, (b) medium or (c) high flow strength. From [2].

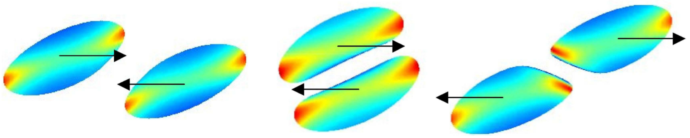

Figure 2: Successive deformed profiles of two capsules crossing in simple shear flow. From [3].

profile. It is then possible to predict the value of the deformation, orientation, rotational frequency and membrane tension level as a function of shear rate and membrane mechanical properties.

This model can be extended to study the hydrodynamic interactions between two identical capsules freely suspended in a simple shear flow [3]. The two particles usually have different velocities and thus eventually overlap and pass each other (fig2). The flow is such that the capsules are not subjected to stress levels leading to burst when they are far apart. However, during crossing, the membranes are submitted to extra strains and stresses that may lead to unexpected break-up. Pair interactions also cause an irreversible cross-flow trajectory shift, indicating a self-diffusion effect in dilute suspensions of capsules.

A limitation of such models is due to the appearance of compressive tensions in the wall and to a tendency towards wrinkling. This phenomenon is consistently observed experimentally. A simple membrane model without bending resistance cannot account for this behaviour and fails when the interface is subjected to compressive tensions for a long time. It is thus necessary to resort to more complex models that account for the bending resistance of the wall [4]. Such models are being developed but at the cost of increased computational time. Another limitation of the model is linked to the use of the Stokes equations that are restricted to Newtonian liquid and inertia-less flows. In order to study the effect of the internal or external liquid rheology or the effect of Reynolds number, a fully 3D approach must be used. The immersed boundary methods seem then quite promising.

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