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Shape Memory of Elastic Capsules Under the Effect of Spontaneous Shape

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Abstract. Red blood cells can recover their resting shape after having been deformed by shear flow. Their rims are always formed by the same part of the membranes, and the cells are said to have shape memory. Modeled as two-dimensional elastic capsules, their recovery motion and shape memory is studied, mainly focused on the effect of the spontaneous shape. The fluid-structure interaction is modeled using immersed boundary method. Based on the simulations, the resting shapes of capsules are obtained and the area ratio of spontaneous shape is found to play an important role. After remove of shear flow, all capsules can recover their resting shapes, while only capsules with noncircular spontaneous shapes present shape memory. As the spontaneous shape approaches a circle but still noncircular, the capsule spends more time on recovery process. We consider how these capsules deform depending on the membrane bending energy, and find that the relaxation speed is positive correlated to the range of values of dimensionless bending energy. These results may help to identify different spontaneous shapes for capsules especially RBCs through future experiments.

AMS subject classifications: 74F10

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1 Introduction

The deformation of fluid-filled capsules and vesicles have been a subject of intense research for many years. Such a structure shares some similar properties with red blood

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cells (RBCs) which are the primary constituent of blood. The flow-induced deformation of an elastic capsule is a fundamental study for further understanding in medical and industrial applications. For example, blood diseases like malaria and sickle cell anemia can stiffen the cell membranes, leading to vascular embolism and hemolysis. The study is also important in design of microcapsules for certain purpose. Experiments and numerical simulations have shown that a single capsule or cell exhibits primarily two types of motion in simple shear flow: tank-treading (TT) motion in which the membrane rotating around the interior fluid while the cell forms a constant angle with the flow direction, and tumbling (TB) motion that the cell rotates like a rigid body [15,17,24]. Further studies revealed the energy barrier for the transition between TT and TB motions [35,38]. The dynamics of capsules and RBCs in various flow conditions have also been observed by experiments or predicted by numerical methods [1,11,14].

Contrary to the deformation of capsules, the recovery motion from deformed states to initial resting shapes draws less interests. Micropipette aspiration [13] and optical tweezing [10] experiments have been used to study the deformation and relaxation of RBC membranes, and the time course of shape recovery shows some behavior consistent with the exponential decay function characterization. For RBCs deformed by shear flow, the relaxation of cell membranes can also been described by the same exponential decay function [4]. The recovery of two-dimensional (2D) biconcave capsules has been predicted numerically, and a two-part recovery is characterized by a pair of exponential decay functions [19].

RBCs exhibit shape memory during the recovery motion subsequent to shear-induced deformation [16]. After the removal of shear flow, the cell can return to its resting shape, and the rim of the cell is always formed by the same part of the membrane. This phenomenon implies that material elements at different position have different natural states, corresponding to some energy minimum shape of the membrane. Similarly, the shear experiments of Dupire et al. [11] and the centrifuge experiments of Hoffman et al. [21] further indicate anisotropic elastic properties of membrane. For RBCs both shear (spectrin network) and bending (lipid bilayer) elasticities might make a contribution to the deformation of the membranes. Thus shape memory could result from spatial inhomogeneous in either the natural state for shear elasticity or for bending elasticity or both.

So far, the main idea for the anisotropy of cell membrane comes from the stress-free state of spectrin network [16,18]. The stress-free state can affect cell dynamics in shear flow and it seems that the stress-free state of RBC is close to a spherical shape [7,28,29]. However, these arguments do not exclude the effect of bending rigidity. The bending energy of membrane is due to the curvature of lipid bilayer, and the spontaneous curvature is imposed to describe the chemical difference between the two monolayers [20]. In the following paragraphs, the term spontaneous shape corresponds to the shape determined by the spontaneous curvature. For capsules with uniform spontaneous curvature shapes (circle and flat plate), it has been shown that bending stiffness cause highly deformed capsules to develop round caps [25,32]. For capsules with resting shapes as spontaneous shapes, the capsules' steady shapes in extension flow are more akin to their resting shapes