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Modeling the Sedimentation of Red Blood Cells in Flow under Strong External Magnetic Body Force Using a Lattice Boltzmann Fictitious Domain Method

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Abstract. Experimental observations show that a strong magnetic field has a dramatic influence on the sedimentation of RBCs, which motivates us to model the sedimentation of red blood cell (RBC) under strong external magnetic body force. To model the sedimentation of a RBC in a square duct and a circular pipe, a recently developed technique derived from the lattice Boltzmann and the distributed Lagrange multiplier/fictitious domain methods (LBM-DLM/FD) is extended to employ the mesoscopic network model for simulations of the sedimentation of a RBC in flow. The flow is simulated by the LBM with a strong magnetic body force, while the network model is used for modeling RBC deformation. The fluid-RBC interactions are enforced by the Lagrange multiplier. The sedimentation of RBC in a square duct and a circular pipe is simulated, which demonstrates the developed method's capability to model the sedimentation of RBCs in various flows. Numerical results illustrate that the terminal settling velocity increases incrementally with the exerted body force. The deformation of RBC has a significant effect on the terminal settling velocity due to the change in the frontal area. The larger the exerted force, the smaller the frontal area and the larger the RBC deformation become. Additionally, the wall effect on the motion and deformation of RBC is also investigated.

AMS subject classifications: 76Z05, 92C35, 92C10

Key words: Sediment, erythrocyte, fictitious domain method, lattice Boltzmann method, flow-structure interaction, red blood cell.

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1. Introduction

Red blood cell (RBC) containing haemoglobin was revealed to be susceptible to magnetic fields [1,2]. The behavior of red blood cells will be greatly affected by strong external magnetic force. Many cardiovascular diseases, such as artherosclerotic disease, strokes, heart attacks, and so on, are related to high blood viscosity. Furthermore, blood viscosity is the key parameter that modulates hemodynamic forces such as shear stress and strain in the vessels, as well as blood pressure. Additionally, hyperviscosity may cause the pre-inflammatory injury that triggers endothelial dysfunction and a cascade of events that result in the hardening and thickening of arterial walls. Hence, reduction of the high blood viscosity is a direct way to reduce the risk of having these diseases or alleviate the potential hardening and thickening of arterial walls. One of the possible means is to impose strong magnetic fields parallel to the blood flow direction. The apparent viscosity would be reduced by 20%$\sim$30% at a magnetic field pulse of 1.3T lasting around 1 min where the RBCs is aggregated along the field direction to form short chain at the microscopic level [3]. Another application of magnetic field is the separation of red blood cell from the blood [2]. High gradient magnetic field is adopted in the process of separation based on the fact that the paramagnetic properties of the reduced haemoglbin [2]. The advantage of using magnetic separation lies in that this magnetic separation is a physical process without the use of additives which may pollute the blood. Thus, it is critical to study the effect of the magnetic fields on the behavior of RBC in fluid flow.

Recently, numerical simulations of red blood cells attract increasing attention because of the important role of RBCs in blood circulation. Simulations of individual RBCs provide a down-to-cell approach to study blood flow. Pioneering and fundamental work conducted by Fung [4], Fung and Zweifach [5], Evans [6], Skalak and Branemark [7], Secomb et al. [8], etc., explored the structure and properties of a RBC membrane and established mathematical RBC models. It is well known that the RBC has no nucleus, and both the cytosol and the plasma are Newtonian fluids. A RBC membrane is composed of a phospholipid bilayer supported by protein skeleton resistant to extension and compression. During the deformation in blood flow, RBCs roughly maintain their surface area and volume. Motion and deformation RBCs in fluid flow are a typical fluid-structure interaction problem where the sub-problems to be solved included the fluid flow, the RBC deformation and motion, the coupling of fluid and RBC interaction and the constitutive equations and models for the fluid and RBC. Many methods were proposed for the flow-structure interactions [4, 8, 10–18]. In this paper, the lattice Boltzmann method (LBM) [19, 20] is employed to solve the flow. The RBC is modeled as a closed membrane filled with cytosol and immersed in plasma. A coarse-grained mesoscopic method developed by Fedosov et al. [11] is used to represent the properties of a RBC membrane, where the spring network model representing the spectrin cytoskeleton of a RBC can be carried out with a coarse mesh to improve computational efficiency. The coupling of flow-RBC interactions is handled by the distributed-Lagrange-multiplier (DLM) based fictitious-domain method, to avoid