International Journal of Engineering Science 95 (2015) 49–59

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Study of blood flow in several benchmark micro-channels using a two-fluid approach

Wei-Tao Wu [a], Fang Yang [b], James F. Antaki [b], Nadine Aubry [c], Mehrdad Massoudi [d,*]

[a] Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[b] Department of Biomedical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[c] Department of Mechanical Engineering, Northeastern University, Boston, MA 02115, USA
[d] U. S. Department of Energy, National Energy Technology Laboratory (NETL), PA 15236, USA

ARTICLE INFO

Article history:
Received 6 January 2015
Received in revised form 1 June 2015
Accepted 15 June 2015

Keywords:
Blood
Micro-channels
Two-component flow
Mixture theory
Shear-thinning
Crevices

ABSTRACT

It is known that in a vessel whose characteristic dimension (e.g., its diameter) is in the range of 20–500 μm, blood behaves as a non-Newtonian fluid, exhibiting complex phenomena, such as shear-thinning, stress relaxation, and also multi-component behaviors, such as the Fahraeus effect, plasma-skimming, etc. For describing these non-Newtonian and multi-component characteristics of blood, using the framework of mixture theory, a two-fluid model is applied, where the plasma is treated as a Newtonian fluid and the red blood cells (RBCs) are treated as shear-thinning fluid. A computational fluid dynamic (CFD) simulation incorporating the constitutive model was implemented using OpenFOAM® in which benchmark problems including a sudden expansion and various driven slots and crevices were studied numerically. The numerical results exhibited good agreement with the experimental observations with respect to both the velocity field and the volume fraction distribution of RBCs.

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1. Introduction

Blood-related diseases, including cardiovascular, cerebrovascular diseases and malaria, are the leading causes of death in the world (Poulter, 1999). For increasing the survival rates of the patients and also improving their life quality, numerous medical devices and therapies have been developed. Their safety and efficacy is intimately related to the properties and behavior of flowing blood. Comparing with the costly experimental trial-and-error, especially at the initial phase of a project, numerical simulations have been emphasized for their high efficiency and low costs in the design of medical devices (Kim, 2012).

Whole blood is a suspension of red blood cells (RBCs), white blood cells (WBCs) and platelets, in plasma. The volume fraction (hematocrit) of RBCs is about 45%, therefore the properties of whole blood is greatly influenced by their rheological behavior. The most prominent properties are their aggregation and disaggregation as a function of shear rate, their deformability, and their alignment responding to extensional flow. For additional detail, the reader is directed to Robertson, Sequeira, and Kameneva (2008), Popel and Johnson (2005), Bäumler, Neu, Donath, and Kiesewetter (1996), Chien (1970) and Wu, Aubry, Massoudi, Kim, and Antaki (2014). These properties are manifested on a bulk scale as shear-thinning and stress relaxation (Bagchi, 2007). At the micro-scale, for example in a vessel whose diameter in the range of 20 to 500 μm (and shear rates

* Corresponding author at: U. S. Department of Energy, National Energy Technology Laboratory, 626 Cochrans Mill Road, P.O. Box 10940, Pittsburgh, PA 15236, USA. Tel.: +1 (412)386 4975.

E-mail address: MASSOUDI@NETL.DOE.GOV (M. Massoudi).

http://dx.doi.org/10.1016/j.ijengsci.2015.06.004
0020-7225/Published by Elsevier Ltd.

below 100 s^{-1}), these non-Newtonian phenomena blood are responsible for the trafficking of RBCs (hence their distribution of volume fraction) (Kameneva, Garrett, Watach, & Borovetz, 1998; Middleman, 1972; Rourke & Ernstene, 1930).

The multi-component features of blood are considered to be important for many blood related phenomena, such as thrombosis and atherogenesis. A thrombus usually refers to a blood clot anchored to damaged vascular walls. The thrombus formation in vivo or in blood wetted medical devices may cause serious health problems or devices malfunction. Several theoretical works related to the modeling of thrombus formation have been done, see (Anand, Rajagopal, & Rajagopal, 2003, 2004; Anand & Rajagopal, 2002; Sorensen, Burgreen, Wagner, & Antaki, 1999a, 1999b). Distribution of the RBCs (red blood cells) influencing the distribution of the platelets due to particles collision is closely related to the thrombus formation (Adams, Fuster, Badimon, Badimon, & Chesebro, 1987; Badimon, Badimon, Turitto, & Fuster, 1987; Badimon, Turitto, Rosemark, Badimon, & Fuster, 1987; Merino, Cohen, Badimon, Fuster, & Badimon, 1994; Sing & Alexander-Katz, 2010). It is known that the thrombus initiation and growth near the walls of the vessels or the medical devices is strongly influenced by the number density of the platelets near the walls (Skorczewski, Erickson, & Fogelson, 2013). Through many mesoscale computational studies, the near wall dense concentration of the platelets is believed to be mainly due to the collisions between the RBCs and the platelets (AlMomani, Udaykumar, Marshall, & Chandran, 2008; Reasor, Mehrabadi, Ku, & Aidun, 2013; Skorczewski et al., 2013). For modeling of the RBCs induced platelets transportation, a multi-component model for blood flow is necessary.

In addition, in the past several decades many important multi-component phenomena have been revealed through the various investigations on blood flow in micro-scale channels. Blood flowing in small tubes exhibits a thin layer of pure plasma, which is called the depletion layer of RBCs (Marhefka et al., 2009), and as a result, plasma-skimming occurs in the branch vessel downstream of the depletion layer (Skalak, Ozkaya, & Skalak, 1989). Because of the depletion of RBCs, this phenomenon may impair transport of oxygen in distal capillaries (Marhefka et al., 2009). The Fahraeus effect occurs when blood flows into a narrow and long vessel from a larger vessel (for vessel diameters ranging from 0.05 to 1.5 mm.) The hematocrit in the narrow tube reduces compared with that of the larger feeding tube (Fahraus, 1929). The Fahraeus–Lindqvist effect is a result of Fahraeus effect, which corresponds to a decrease of the viscosity in the narrow tube compared with that of the feeding (larger) tube (Fahraus & Lindqvist, 1931). In summary, it is evident that blood flow at micro-scales acts as a multi-component material, and exhibits more complex behavior than can be described by a single component model.

In the past several decades, various multi-component models for blood have been developed. Mesoscale simulations, such as the *Immersed Boundary Method* (IBM) combined with the *Lattice Boltzmann Method* (LBM), are useful methods for investigating the complex behavior of blood or RBCs in micro-scale flow, particularly due to the deformation, aggregation of the RBCs (see Clausen, Reasor, & Aidun, 2010; Dupin, Halliday, Care, Alboul, & Munn, 2007; Zhang, Johnson, & Popel, 2009). In these studies, the RBC cytoskeleton and membrane are modeled as a network of springs in combination with bending rigidity and constraints for surface-area and volume conservation. The fluid forces experienced by RBCs are then calculated by integrating the pressure and shear stresses along the RBCs surface (Pan, Fedosov, Caswell, & Karniadakis, 2011). Although these mesoscale simulations have been useful in displaying non-Newtonian behavior of blood, they are still prohibitive for industrial and engineering scale simulations due to the high computational cost (Van der Hoef et al., 2006). An alternative method, the two-fluid approach or the two component model overcomes the limitation of high computational cost but still provides useful information, such as the volume fraction distribution of the RBCs (Jung, Hassanein, & Lyczkowski, 2006; Jung & Hassanein, 2008). For the two-component formulation, two methods have been widely used: the *Averaging Method* (see Gidaspow & Huang, 2009; Huang, Lyczkowski, & Gidaspow, 2009; Ishii, 1975) and *Mixture Theory* (or the Theory of Interacting Continua) which is applied in the current paper (Rajagopal & Tao, 1995). The mixture theory is a homogenization approach within the framework of continuum mechanics, first presented by Truesdell (1957), in which the phenomena of diffusion, dissociation, combination, and chemical reaction in the broadest sense can be represented (Truesdell, 1984). For the basics of the theory, the historical development and applications, the reader is directed to review articles by Atkin and Craine (1976a, 1976b), Bowen (1976), Bedford and Drumheller (1983), Massoudi (2008, 2010), and the books by Truesdell (1984) and Rajagopal and Tao (1995).

A two-fluid model for blood, based on mixture theory, was previously introduced (Massoudi & Antaki, 2008), and further detailed in Massoudi, Kim, and Antaki (2012) and Wu, Aubry, and Massoudi (2013, 2014), The model treats plasma as a Newtonian fluid while the RBCs are treated as a shear-thinning fluid whose viscosity depends on the volume fraction according to experimental observations of Brooks, Goodwin, and Seaman (1970). For studying this two-component system, a three dimensional CFD solver is implemented based on the solvers and libraries in the OpenFOAM®.

2. Methods

2.1. Governing equations

In the absence of thermo-chemical and electromagnetic effects, the governing equations consist of the conservation of mass, linear momentum and angular momentum. The equations for the conservation of mass in the Eulerian form are (see Bowen, 1976),

$$\frac{\partial \rho_f}{\partial t} + div\left(\rho_f \boldsymbol{v}_f\right) = 0 \tag{1}$$

$$\frac{\partial \rho_{rbc}}{\partial t} + div(\rho_{rbc} \boldsymbol{v}_{rbc}) = 0 \tag{2}$$