International Journal of Heat and Mass Transfer 113 (2017) 840–849

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

The effect of red blood cells on blood heat transfer

Haiwei Xie, Yan Zhang *

School of Mechanical Engineering, Tianjin University of Commerce, Tianjin 300134, PR China
Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin 300134, PR China

ARTICLE INFO

Article history:
Received 21 February 2017
Received in revised form 21 May 2017
Accepted 27 May 2017

Keywords:
Two-phase fluid
Micro-particle dynamics
Heat transfer efficiency
Red blood cell
Pulsatile flow

ABSTRACT

In an attempt to analyze the effect of red blood cells on heat transfer, a two-phase flow heat transfer model of flowing blood was proposed in this paper. In this model, blood is treated as a two-phase fluid composed of red blood cells as the particle phase and plasma as the carrier fluid. The micro-particle dynamics, including aggregation, deformation, mutual collisions of red blood cells and relative movement of red blood cells to plasma, are considered by some equations or simplified methods. The velocity field, temperature field, fluid viscosity and volume fraction of red blood cells in a two-phase blood flow can be calculated using this model. To verify the accuracy of the simulation results of the model, the velocity distribution and heat transfer efficiency calculated by this model were compared with available experimental data from the literature. Good agreement was obtained between these data; thus, this model can accurately simulate the blood flow and heat transfer in a vessel. Then, the model was used to analyze how the micro-particle red blood cells affect the heat transfer of blood, and red blood cells were found to enhance heat transfer efficiency of blood. The viscosity properties of blood, the solid pressure and the lateral movement of red blood cells are the important determinants of this enhancement. The influence of red blood cells on the heat transfer efficiency of pulsatile blood flow was also calculated using this model.

1. Introduction

As the thermoregulation theory of the human body [1] and modern clinical medical technologies, such as cryosurgery [2], heat therapy [3], and thermal diagnosis of disease [4], are developing rapidly, biological temperature prediction has become a common research method in biomedical engineering. There is a complicated coupling relationship in the heat transfer process between biological tissue and blood circulation. Investigating the influence of the heat transfer of blood vessels plays an important role in simulating temperature distribution in biological tissue.

Blood is composed of plasma (Newtonian fluid), RBCs (red blood cells) and other micro-particles, in which the deformable RBCs account for greater than 99% of the total volume of particulate matter. Thus, blood is often treated as a suspension of RBCs in plasma. Numerous haemodynamic studies indicate that RBCs have a significant impact on blood flow characteristics and have a certain correlation with the occurrence of some diseases. Chien et al. [5,6] demonstrated that the RBC aggregates, which are a result of cell-protein interactions, are the major mechanism responsible for the shear-thinning behaviour of whole blood at a low shear rate; the shear deformation of the deformable RBC is another factor leading to the shear thinning of blood under a high shear rate. The aggregation of RBCs and leukocytes in the blood plays a key role in atherosclerosis formation [7]. Jung et al. [8] numerically analyzed the flow field in the curved blood vessel using a two-phase shear-thinning model of blood. Their results demonstrated that RBC aggregation occurs on the inside curvatures of arteries, which provides evidence for understanding the formation of atherogenesis, given that clinical observations indicate that atherosclerotic plaques typically form on the inside flexures of arteries.

The RBCs suspended in blood affect the blood flow field. Given that heat transfer and blood flow are coupled, RBCs may also have an impact on the heat transfer of blood. It is generally believed that the rate of transverse heat transfer in two-phase suspension is higher than the rate in the suspending medium alone due to the lateral movements, collisions, and rotations of particles. Leal [9] has analyzed the heat transfer in the suspension of deformable liquid drops in the limit of low Pecelt numbers and proposed an effective transverse thermal conductivity formula that includes the effect of particles on heat transfer.

* Corresponding author at: School of Mechanical Engineering, Tianjin University of Commerce, Jinba Road East Inlet, Tianjin, PR China.

E-mail address: zhy@tjcu.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.112
0017-9310/

Nomenclature

c	specific heat
d_s	diameter of red blood cell
e_{ss}	restitution coefficient for RBCs collisions
F_{lift}	lift force
$g_{0,ss}$	RBC radial distribution function
Gz	Graetz number
h	distance of the RBC centre to vessel wall
h_{sf}	volumetric heat transfer coefficient
k	thermal conductivity
k_{sf}	interphase momentum exchange coefficient
Nu	Nusselt number
Pe	Pecelt number
Pr	Prandtl number
p_s	solid pressure of RBCs
r	radial distance from vessel axis
r_0	radius of blood vessel
Re	Reynolds number
t	time
T	temperature
u_{in}	inlet flow velocity
u_m	cross-section mean velocity
$\vec{v}$	velocity vector
Greek symbols	
α	volume fraction
$\alpha_{s,\max}$	maximum volume fraction of RBCs in blood
ε	heat transfer efficiency
ρ	density
η	viscosity
η_1	viscosity of suspending medium
η_2	viscosity of suspending droplet
η_{rel}	dimensionless relative viscosity
$\dot{\gamma}$	shear rate
$\bar{\bar{\tau}}$	stress tensor
Θ_s	granular temperature
Subscripts	
s	RBCs
f	plasma

$$K^* = k\left[1 + 0.12\alpha\left(\frac{2\eta_1 + 5\eta_2}{\eta_1 + \eta_2}\right)^2 Pe^{2/3}\right] \tag{1}$$

To study the enhancement of heat transfer caused by RBCs in suspension, numerous experiments on blood heat transfer have been performed and published, but significant differences among the conclusions of these studies are noted. Some researchers have observed that the heat transfer enhancement of blood due to RBCs is very small and can be neglected. Mitvalský [10] performed a cooling experiment using diluted human blood and found that the Nu of blood heat transfer is only dependent on Gz, $Nu = 1.81\,Gz^{1/3}$, similar to Newtonian fluid. Ahuja and Hendee [11] have performed extensive experiments on heating and cooling blood using dog or turtle blood as the object of investigation and reported that the rotation of RBCs has no measurable effect on blood heat transfer. However, other researchers draw the opposite conclusion. Carr and Tiruvaloor [12] performed heating and cooling heat transfer experiments using blood cell suspensions, and results were compared with water. Heat transfer is enhanced significantly for blood cell suspensions, and the heat transport rates of heating blood are increased compared with cooling blood. Wang and Keller [13] believe that the heat transfer augmentation of erythrocyte suspensions is correlated with the Peclet number. According to their experiment, the effective heat transfer coefficient formula is obtained for a 0.4 haematocrit RBC suspension, Eq. (2), which is consistent with reported experimental results regarding the transport of heat and micro-particles, such as urea, albumin, and platelets in flowing blood.

$$K^* = k[1 + 0.061Pe^{0.89}] \tag{2}$$

Why are the two conclusions so divergent? How do RBCs affect the heat transfer of flowing blood, and how large is the influence? To analyze these problems, a two-phase flow heat transfer model of flowing blood is established in this paper. In this model, blood is treated as a suspension of RBCs in plasma, and the flow and heat transfer process of blood is described by two-phase flow equations. The micro-motions of RBCs, including deformation, aggregation and mutual collisions, are all expressed by some simplified methods in this model, according to the relevant research results of RBCs in flowing blood. Heat transfer of flowing blood in a straight vessel in multiple cases has been simulated by the model. The influence of the micro-motions of RBCs on heat transfer efficiency in steady and macro-pulsation blood flow were analyzed.

2. Flow and heat transfer model of blood

2.1. Mathematical formulations of two-phase flow model

Two main types of methods are available to simulate the RBCs in the flowing blood model. In the first method, RBCs are treated as pseudo-fluid, and blood flow is simulated by the Eulerian model of multiphase flow [8,14]. In the second method, erythrocytes are regarded as suspended particles in plasma. Descriptions of the shape and mechanical properties of each erythrocyte are provided, and the blood suspension is simulated using the lattice-Boltzmann method [15–17]. Obviously, the second method more accurately reflects the actual situation of blood. However, the computation work of this method is very large. This method is mainly applied to the simulation of the capillary or arteriole, in which the number of RBCs is not too large. In this paper, the research objects are the thermally significant blood vessels of medium diameter with large numbers of RBCs. Therefore, the flow and heat transfer model of blood proposed in this paper uses the first method; namely, blood is treated as a two-phase fluid composed of plasma (Newtonian fluid) and RBCs (pseudo-fluid). The mathematical formulations of this model are as follows.

Conservation equation of mass:

$$\frac{\partial(\alpha_i\rho_i)}{\partial t} + \nabla\cdot(\alpha_i\rho_i\vec{v}_i) = 0 \tag{3}$$

where i is s (RBCs) or f (plasma), $\alpha_s + \alpha_f = 1$.

Conservation equation of the momentum of plasma:

$$\frac{\partial(\alpha_f\rho_f\vec{v}_f)}{\partial t} + \nabla\cdot(\alpha_f\rho_f\vec{v}_f\vec{v}_f) = -\alpha_f\nabla p + \alpha_f\rho_f\vec{g} + \nabla\cdot\bar{\bar{\tau}}_f + k_{sf}(\vec{v}_s - \vec{v}_f) + \vec{F}_{lift,f} \tag{4}$$

Conservation equation of the momentum of RBCs: