International Journal of Thermal Sciences 64 (2013) 40–52

Contents lists available at SciVerse ScienceDirect

International Journal of Thermal Sciences

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

Effect of magnetic field on temperature distribution of atherosclerotic plaques in coronary artery under pulsatile blood flow condition

S. Ghaffari [a,*], S. Alizadeh [b], M.S. Karimi [a]

[a] Mechanical Engineering Department, College of Engineering, University of Tehran, Tehran 14399-56191, Iran
[b] Mechanical Engineering Department, Stanford University, Stanford, CA, USA

ARTICLE INFO

Article history:
Received 25 November 2011
Received in revised form
12 July 2012
Accepted 5 September 2012
Available online 11 October 2012

Keywords:
Atherosclerotic arteries
Multi-directional magnetic field
Inflammatory cell
Arterial wall temperature
Curvilinear coordinate
Pulsatile flow
Magnetohydrodynamic (MHD)

ABSTRACT

Temperature heterogeneity in plaque containing inflammatory cells can cause thermal stress, and speeds up plaque growth or rupture process. Activated inflammatory cells embedded in plaques release heat while the plaque is cooled by blood flow. In the present work, arterial wall temperature distribution of atherosclerotic Right Coronary in the presence of external uniform and multi-directional magnetic field is investigated by numerical methods. The magnetic field is applied in both x and y directions. An advanced coupled FEM–FVM algorithm is used to determine temperature distribution inside the artery. Transient Navier–Stokes and energy equations in 2D idealized arterial model of a bending artery coupled with Maxwell's equations are discretized using the Finite-Volume Method and solved by SIMPLE algorithm in curvilinear coordinate to analyze pulsatile blood flow, whereas the transient heat conduction equation in the plaque is solved simultaneously with these equations using Finite-Element Method. The plaque temperature, Nusselt Number and heat flux at the plaque/lumen interface is obtained for various moments of cardiac cycle and different states of magnetic field to investigate influence of produced electromagnetic force on the cooling effect of blood. It is observed that how magnetic field modifies the temperature heterogeneity of plaque and decreases probability of rupture of Atherosclerotic plaque.

1. Introduction

Atherosclerosis which is responsible for most heart problems refers to a degenerative disease of the arteries characterized by patchy thickening of the inner lining of the arterial walls, caused by athermanous plaques which are made of fatty substances, cholesterol, waste products from the cells, calcium, and fibrin.[1] Moreover, the local velocity, the molecular viscosity disturbances and the morphological[2] particularities may also predispose to the formation of coronary atheromatic plaques [1,2]. The inner layer of the artery wall thickens by means of plaques, the artery's diameter is reduced, and blood flow and oxygen delivery are decreased. The heat produced by metabolic activities of macrophages or inflammatory cells embedded in plaque results in a rise in plaque temperature. Sometimes the blood flow as cooling mechanism is not able to reduce the temperature in hot spots and as a result the existent plaque is prone to rupture or crack open, causing the sudden formation of a blood clot.[3] Such plaques which are usually seen in segments of arteries where the occurrence of flow separation and formation of secondary and recirculation flows are common [3–6], are classified as vulnerable ones and they are characterized by the parameters affecting temperature heterogeneity such as thickness of plaque, density of macrophage cells, length and depth of macrophage layer embedded in plaque [7]. This phenomenon can cause a heart attack if it completely blocks the blood flow in the heart arteries. It can also cause a stroke if it completely blocks the brain arteries.

So far, a considerable amount of works, both theoretical and experimental on this interesting and serious problem were carried out and by means of these efforts some of the mysteries about it were discovered. There have been several observations on the effects of shear stress on the biological functions of endothelial cells[4] that indicate that exposure of endothelial cells to moderate-to-high shear stresses prevents atherogenesis in cholesterol-fed monkeys [8] and enhances the synthesis of prostacyclin and uptake of low density lipoproteins by endothelial cells in culture.

* Corresponding author. Tel.: +98 9125031913; fax: +98 218833 0050.
E-mail addresses: siavashghaffari@yahoo.com, sghaffari@ut.ac.ir (S. Ghaffari).

[1] A stringy material that helps clot blood.
[2] Geometrical.
[3] Thrombosis.
[4] Cells that lines the interior surface of blood vessels.

1290-0729/$ – see front matter
http://dx.doi.org/10.1016/j.ijthermalsci.2012.09.001

Nomenclature

B	Magnetic field vector (Weber/m^2)
C_p	Blood specific heat (j/kg K)
D_0	Artery diameter (m)
E	Induced electric field and polarization of charges (v/m)
Ec	Eckert number
F_m	Electromagnetic force (N)
Ha	Hartmann number
J	Current density (A/m^2)
k	Blood thermal conductivity (W/m K)
Nu	Nusselt number
P	Blood pressure (N/m^2)
Pr	Prandtl number
q''	Heat flux
Re	Reynolds number
t	Time (s)
T	Blood temperature (°C)
T_b	Normal body temperature
T_{ave}	Average temperature
T_s	Plaque surface temperature
u	x-component of velocity (m/s)
U_0	Uniform velocity inlet (m/s)
v	y-component of velocity (m/s)
V	Velocity vector (m/s)
W_{mag}	Work done by electromagnetic force (J)
x, y	Cartesian directions
μ	viscosity coefficient (kg/m s)
p	Blood density (kg/m^3)
α	Electrical conductivity (1/Ω m)
τ	Shear stress (N/m^2)

Chambless et al. [9] studied the relation between carotid artery intima-media thickness (IMT) and increased risk of coronary heart disease (CHD). In 1997 they obtained this fact that up to 1 mm mean IMT, women had lower adjusted annual event rates than men did, but above 1 mm their event rate was closer to that of men. In 2000 Shigeo Wada et al. [10] found out in a straight artery, accumulation of LDL occurs near the vessel wall depending the magnitude of shear rates, filtration velocity at the vessel and diffusivity of LDL in blood. They also applied a curved blood vessel and other geometries and showed that LDL concentration increases locally in curved segments. In a multiple bending artery they realized that due to a semipermeable nature of an arterial wall to plasma, flow-dependent concentration polarization of LDL occurred at the luminal surface of the vessel, creating a region of high LDL concentration distal [3].

To demonstrate the severe effect of plaque on temperature distribution, Diamantopoulos et al. [11] investigated the relation between acute coronary flow reduction and arterial wall temperature. They observed that there is a threshold of average peak velocity (APV) for this relation. The effect appears only below a critical threshold of APV and above this threshold, temperature measurements should be unaffected from flow reductions and related to the regional temperature heterogeneity. In 2004 Ten Have et al. [12] concentrated on thermography method to find the temperature distribution. This study shows that correct interpretation of intravascular thermographic measurements requires data on the flow and on the morphologic characteristics of the atherosclerotic plaque. In another study [13], they evaluated the plaque geometry and flow effect on the temperature distribution in an atherosclerotic artery. Considering a plaque as a heat source, they found out as the plaque geometry increases, the maximal temperature differences at the lumen wall rises and the influence of flow as coolant is highest for circumferentially extended plaques compared with longitudinally extended sources. Moreover, Obdulia Ley and Taehong Kim [14,15] applied a numerical method using COMSOL analysis to find temperature distribution in a bending artery and concluded that the best location to perform the temperature measurement is at the back region of the plaque. Also, they observed that the location of the maximum temperature or hot spot at the plaque surface can move during the cardiac cycle depending on the arterial geometry and is a direct result of the blood flow pattern.

Among works in this area, some have concentrated on the positive effect of magnetic field on the blood flow in atherosclerotic arteries. Tzirtzilakis has worked on mathematical models for biomagnetic fluids and analyzed the blood flow inside a straight rectangular duct [16–18]. Their numerical solution verified the sensibility of blood flow and its reaction to the external field. From the most recent study of Tzirtzilakis significant conclusion is that the flow velocity, the temperature field, the skin friction and the rate of heat transfer all are influenced by the magnetic field remarkably [19]. A more accurate project was conducted by Ikbal et al. [20]. Considering the blood flow as a non-Newtonian flow and also applying a one dimensional magnetic field to this biomagnetic fluid, they evaluated the effect of some parameters including Hartman number to flow velocity and shear stress and validated their results with discovered facts in previous literatures.

The review of the previous works shows that numerous studies were conducted on flow characteristics and calculation of arterial wall temperature in atherosclerotic vessels. However, according to the authors' knowledge, there are a few studies of thermal investigation of atherosclerosis in anatomically realistic arterial model and also there are a few studies of investigation of effect of magnetic field on the stenosis. The present investigation is devoted to study the investigation of effect of external uniform and multi-directional magnetic field on arterial wall temperature distribution atherosclerotic right coronary which is considered as an anatomically realistic arterial model. The right coronary artery is one of two blood vessels that branch from the aorta and carry oxygen-rich blood to the heart muscle. Blockage of any branch of the coronary arteries causes death of a portion of the heart. The calculations are performed under the pulsatile inlet blood flow which necessitates an unsteady analysis.

2. Mathematical formulation

In this study a realistic model of atherosclerotic right coronary artery is assumed as the geometry of the problem and inside the vessel the blood as a Newtonian incompressible fluid flows over the plaque. Newtonian assumption is justified for a large artery which is used in this analysis [21,22]. The geometry is presented in Fig. 1 in which $D = 3.53$ mm and $L_p = 3$ mm (the plaque length).

2.1. Governing equations for blood flow

The fluid surface interaction is neglected which regarding to other works make a negligible error [23–25]. Moreover, to consider the pulsatile blood flow effect, the unsteady form of continuity, Navier–Stokes and energy equations are applied on the flow inside the artery. The last term in Navier–Stokes equation and its resultant work in energy equation are created in presence of external