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Evaluation effect of magnetic field on nanofluid flow through a deformable bifurcated arterial network

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ABSTRACT

We applied a modified unsteady two-phase flow model for the first time to describe the hemodynamic and thermal behaviors of flow in a realistic bifurcation structure incorporated with flexibility phenomena. A current-carrying wire magnetic field was introduced vertically nearby the flexible vessel to determine the effect of the interaction between flowing nanofluid (blood and 3% (*w/v*) Fe_3O_4) and flexible wall. The pressure and vorticity profiles along the flexible segment, as well as the velocity and temperature of fluid taking at the middle line of the collapsible vessel were analyzed during move-up or move-down of the flexible arterial wall. The results reveal that the profiles of pressure and vorticity are increased and decreased respectively for different current intensities. Also, the effect of the magnetic field with different current intensities moves the elastic vessel wall outwardly that leads to the resistance on the flow field considerably. Thus, the current-carrying wire magnetic field can shift the local maximum velocity toward the flexible vessel wall. These results can be beneficial for curing the vascular clogging of vessel based nano-drug delivery system.

1. Introduction

The exploration phenomena of flow through collapsible elastic ducts are essential not only in clinical medicine but also for physiological fluid mechanics. These characteristics usually occur to the function of the human bodies such as blood flow through veins and arteries, air flow through lungs, fluid flow through the urethra, and food flow in pharynx, esophagus and small intestine [1,2]. Moreover, flow features through flexible ducts are illustrated by the interaction between duct distortion and fluid, and flow-induced applied pressures [3]. However, it is poorly understood such type of salient flow features through elastic vessels because the variation of the deformable wall shape cannot be anticipated in advance. Therefore, modeling study is crucial to ascertain the deformation of the vessel wall under pressure driven fluid flow.

Several studies led to determine the flow features through collapsible elastic tubes experimentally and numerically. For example, Lyon et al. [4] proposed a waterfall model and conducted the experiment based on Starling resistor model to describe the flow arena through a deformable duct for low Reynolds number (i.e., $Re < 1$). Pedley [5] also presented a two-dimensional Starling resistor model that was mainly focused on numerical studies based lubrication theory. Rast [6] recommended a tube model with a portion of upper wall replaced by a flexible membrane aspect and solved the fluid-elastic membrane equations using the Newton-Raphson method. The results revealed that the membrane wall distorted dramatically for higher Reynolds number (i.e., $Re = 300$). Luo and Pedley [7] considered a parallel-sided rigid channel including an exemplary elastic membrane interface, and solved numerically under the governing factors (e.g., pressure, tension, and Reynolds number). The observable distended phenomena were found at the upstream end of the flow channel throughout the coupled fluid-membrane modeling study. Besides, two-dimensional collapsible models were presumed to investigate the steady and unsteady flow characteristics and solved the fluid-membrane model [8,9] or fluid-beam model [10,11] using different methods. Their results revealed that the typical collapsible models were efficiently formed the self-excited oscillations phenomena. Some studies offered to understand the dynamic self-excited behaviors of such flexible tubes as well [12–17].

Nanofluids, especially magnetite nanofluids, are colloidal solutions made of magnetic nanoparticles (Fe_3O_4) with a typical diameter of 10 nm dispersed in a suitable base fluid. Moreover, magnetic nanoparticles (MNPs) are designated as drug carriers and used for the treatment of various cancerous and non-cancerous diseases owing to its

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Nomenclature

Symbol

δ	Arterial vessel diameter [mm]
n	Bifurcation exponent
ℓ	Arterial vessel length [mm]
θ	Bifurcation angle [°]
$\mathbf{u}$	Mass-averaged velocity [m·s^{-1}], $\mathbf{u}_m = \frac{\alpha_p \rho_p \mathbf{u}_p + (1-\alpha_p)\rho_f \mathbf{u}_f}{\rho_m}$
q	Number of phases
$\mathbf{u}_{dr,q}$	Drift velocity [m·s^{-1}], $\mathbf{u}_{dr,\ q} = \mathbf{u}_q - \mathbf{u}_m$
$\mathbf{u}_{pf}$	Slip velocity [m·s^{-1}], $\mathbf{u}_{pf} = \mathbf{u}_p - \mathbf{u}_f$
$\mathbf{g}$	Gravitational acceleration [m·s^{-2}]
P	Pressure [Pa]
k_m	Mixture thermal conductivity [W·m^{-1}·K^{-1}]
c_p	Specific heat [J·kg^{-1}·K^{-1}]
t	Time [s]
T	Temperature [K]
$\mathbf{F}$	Kelvin force [N·m^{-3}]
$\mathbf{H}$	Magnetic field intensity [A·m^{-1}]
$\mathbf{M}$	Magnetization [A·m^{-1}]
M_s	Saturation magnetization [A·m^{-1}],$M_s = \frac{6\alpha_p m_p}{\pi d_p^3}$
La(ζ)	Langevin function, $La(\zeta) = \frac{1}{\tanh(\zeta)} - \frac{1}{\zeta}$
m_p	Particle magnetic moment [A·m^2], $m_p = \frac{4\mu_B \pi d_p^3}{6 \times 91.25 \times 10^{-30}} A \cdot m^2$
d_p	Magnetic particles diameter [m]
k_B	Boltzmann constant [J·K^{-1}], $k_B = 1.3806503 \times 10^{-23}$ J·K^{-1}
H	Magnitude of magnetic field intensity, $H(x,y) = \frac{I}{2\pi}\frac{1}{\sqrt{(x-a)^2+(y-b)^2}}$
I	Electric current intensity [A]
P_e	External pressure [Pa]
T_m	Surface tension of membrane [N·m^{-1}], $T_m = 0.0322$ N·m^{-1}
R	Membrane's radius of curvature
U_0	Inlet velocity [m·s^{-1}]
T_c	Inlet temperature [K], $T_c = 300$ K
T_h	Temperature of arterial vessel wall [K], $T_h = 310.15$ K
x, y	Cartesian coordinates [m]

Greek symbol

ρ_m	Density [kg·m^{-3}]
α_q	Volume fraction
μ_0	Magnetic permeability in a vacuum state [T·m·A^{-1}], $\mu_0 = 4\pi \times 10^{-7}$ T·m·A^{-1}
μ_B	Bohr magneton [J·T^{-1}], $\mu_B = 9.27 \times 10^{-24}$ J·T^{-1}
ζ	Langevin parameter, $\zeta = \frac{\mu_0 m_p H}{k_B T}$
μ_m	Dynamic viscosity [kg·m^{-1}·s^{-1}]
∇	Nabla operator, $\nabla = \mathbf{i}\frac{\partial}{\partial x} + \mathbf{j}\frac{\partial}{\partial y}$
η	Variable for convergence criterion
ε	Tolerance

Subscripts

m	Mixture phase
f	Biofluid phase
p	Particles phase
e	External
s	Saturation
0	Initial state

Superscript

τ	Iteration number

high efficiency, minor toxicity and little side effects on healthy cells and tissues compared to conventional chemotherapy [18–20]. MNPs are offered for the improvement of drug steadiness, bioavailability, targeting and biological activity as well [19,21–24]. Consequently, the nano-drug delivery system can eradicate disease tissues when magnetic nanoparticles inserted into the bloodstream as a carrier of therapeutic agents. Further, a typical local magnetic field affects the bloodstream as well as induces the magnetic drug carrier particles at a specific region in the human body [21,22,25,26]. Besides, biofluid (i.e., blood) itself behaves as a magnetite nanofluid owing to the sophisticated phenomena including the hemoglobin, cell membrane, and the intercellular protein. In this contexts, Loukopoulos and Tzirtzilakis [27] proposed a numerical model to investigate the flow characteristics of biomagnetic (blood) fluid under the magnetic field. They considered the linear variations in magnetization of fluid concerning the magnetic field strength and temperature and solved numerically using finite difference method. The results revealed that when the magnetic source situated near the bottom channel wall, a typical vortex is generated inside the flow domain with upsurge the magnetic number. Ganguly et al. [28] focused on the modeling study of fluid flow through the rectangular channel by a line-source dipole. They found that thermal behaviors upsurge with the impact of the dipole numbers and the higher magnetic field strengths. The other simulation study employed the multiphase model to describe the fluid flow and heat transfer characteristics for a kerosene-based ferrofluid in cylindrical geometry as studied in Jafari et al. [29]. Their results indicate that the existence of the magnetic field impacts the flow arena significantly and heat transfer rises with applied magnetic field perpendicular to the gradient of temperature. Further, several studies explored the impact of magnetic field on fluid flow and heat transfer features in different geometries of the rectangular duct, annuli, cylinder, stenosis, and aneurysm [30–40]. These investigations disclosed that magnetic fields enhance the transport processes, and the thermal characteristics inside flow domains are governed by the impacts of the typical magnetic field and the gradient of temperature.

Some of the prior studies reported on analyze biofluid flow and its hydro-thermal characteristics in human bifurcation model. In this viewpoints, Yang et al. [41] studied the fluid-structure interaction (FSI) approach in an arterial bifurcation channel to account for the interaction between the flowing blood and the deforming arterial wall. Their results demonstrated that deformation phenomena augment the resistance on the fluid flow through the flexible artery. Khakpour and Vafai [42] discussed the hemodynamic factors (e.g., Wall shear stress) for aorta-iliac bifurcation model. Yang et al. [43] also investigated the expiratory flow behaviors through a symmetric three generation airway model and found the secondary flow structure of different Reynolds numbers. The dimension and placement of a rigid bifurcated vessel change the heat transfer phenomena during magnetic fluid hyperthermia treatment as illustrated in Yue et al. [44]. Larimi et al. [45] studied the biofluid flow and magnetic nanoparticles features by applied magnetic field along a rigid branched vessel. Their results revealed that volume fraction of particles (i.e., delivered to target region) decreased by increasing the Reynolds number. Zhang and Xie [46] numerically studied the convective heat transfer phenomena of a rigid branched vessel structure and discussed the Nusselt number effect between parent vessel and symmetric children vessel. Luo et al. [47] found that when the length of the branched structure increases, the heat transfer rate decreases. Recently, a numerical simulation scheme presented by Zhang and Xie [48] to investigate the effect of flow and heat