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Full Length Article

Flow of a Bingham fluid in a porous bed under the action of a magnetic field: Application to magneto-hemorheology

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ABSTRACT

The study deals with an investigation of the flow of a Bingham plastic fluid in a porous bed under the action of an external magnetic field. Porosity of the bed has been described by considering Brinkman model. Both steady and pulsatile motion of this non-Newtonian fluid have been analysed. The governing equations are solved numerically by developing a suitable finite difference scheme. As an application of the theory in the field of magneto-hemorheology, the said physical variables have been computed by considering the values of the involved parameters for blood flow in a pathological state, when the system is under the action of an external magnetic field. The pathological state corresponds to a situation, where the lumen of an arterial segment has turned into a porous structure due to formation of blood clots. Numerical estimates are obtained for the velocity profile and volumetric flow rate of blood, as well as for the shear stress, in the case of blood flow in a diseased artery, both the velocity and volumetric flow rate diminish, as the strength of the external magnetic field is enhanced. The study further shows that blood velocity is maximum in the plug (core) region. It decreases monotonically as the particles of blood travel towards the wall. The study also bears the potential of providing numerical estimates for many industrial fluids that follow Bingham plastic model, when the values of different parameters are chosen appropriately.

1. Introduction

Hemorheology (also called as blood rheology) deals with various flow characteristics of blood and its constituents, e.g. plasma, erythrocytes (red cells), white cells, platelets, etc. Tissue perfusion can take place properly, as long as the rheological properties of blood are well within certain levels. Significant departures of the properties of blood from those at the normal physiological state may lead to different arterial diseases. Many health problems, including hypertension, diabetes mellitus and insulin resistance, metabolic syndrome and obesity are directly linked with the viscosity of whole blood. The area of studies related to the rheological properties of blood under the action of magnetic fields (as in the case of MRI) may be called as magneto-hemorheology.

Human exposure to external magnetic fields is of common occurrence in various clinical procedures. Patients are exposed to strong magnetic fields during MRI (magnetic resonance imaging). An excellent review of various issues related to the exposure of humans to static magnetic fields of high intensity during MRI was presented by Schenck [1]. He made an important observation that there is hardly any evidence of health hazard associated with exposure of the human body to magnetic fields, not even when the body is exposed to a strong magnetic field in a cumulative manner, provided no ferromagnetic material is present. The reason behind this observation is twofold: (i) Human tissues lack ferromagnetic materials, and (ii) magnetic susceptibility of these tissues is small.

As mentioned by Schenck [1], studies on human subjected to a magnetic fields of strength up to 8 T and on sub-human under the action of magnetic fields up to 16 T indicate that a considerable margin of safety exists. This observation shows that the range 3–4 T commonly used in clinical procedures is well within the safety zone.

It is known that blood is an electrically conducting fluid and so when blood flows under the action of an external magnetic field of sufficient strength, a transverse EMF is developed, which is directly proportional to the velocity of blood, as well as to the intensity of the applied magnetic field. Owing to this, it becomes difficult to obtain good ECGs during magnetic resonance scanning. Kinouchi et al. [2] pointed out that the said effect contributes to human tolerance of highly intensified magnetic fields.

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Nomenclature

r^*, ϕ^*, z^*	cylindrical co-ordinates	$P(t)$	non-dimensional pressure gradient
R^*	radius of the tube	$k(r)$	permeability factor
r_p^*	radius of plug region	α	Womersley parameter
R_0	characteristic radius	A	amplitude of the flow
u^*	velocity in radial direction	w	angular frequency
u_c	characteristic velocity	B_0, σ	magnetic induction and conductivity of the medium
ρ, μ	density and viscosity, respectively	M	Hartmann number
τ^*	shear stress		
τ_c^*	characteristic shear stress		
τ_y^*	yield stress		

Bingham plastic fluids are those in which the excess deviatoric stress over the yield stress varies linearly with shear rate. These fluids exhibit non-Newtonian behavior. They bear the potential to transmit shear stress even in the absence of a velocity gradient. There exists a linear relationship between shear stress and strain for Bingham plastic fluids; a finite yield stress is needed for them to flow. At a low stress level, their motion is very similar to that of a rigid body, but when the stress level is high, they flow like a viscous fluid. It has been found that Bingham liquids possess thicker coating in comparison to the case of Newtonian fluids. Clay, drilling mud, printing ink, molten liquid crystalline polymers, foams, paint, toothpaste and food articles like margarine, mayonnaise, molten chocolate, yoghurts and ketchup are some typical examples of Bingham plastics. Since Bingham fluids are transformed to solids when the applied shear stress is less than the yield stress, it is apparent that Bingham fluids behave like a solid medium in the core layer. That means, a solid plug moves within the flow.

A study on the settling characteristics of spherical particles in Bingham plastic fluids was conducted by Ansley and Smith [3]. Mitsoulis [4] presented a review of research activities of viscoplastic models that include Bingham plastic model, Herschel–Bulkley model and Casson model. He discussed, in particular, the entry and exit flows from dies, flows around spheres and cylinders, as well as squeeze flows. A theoretical study of the free convection in a Bingham plastic fluid on a vertical flat plate with constant wall temperature was performed by Kleppe and Marner [5]. They reported that Bingham plastic friction coefficients are considerably higher than those in the case of Newtonian fluids. This increase was attributed to the yield stress of Bingham plastic fluids. A two-dimensional study on creeping flow of a Bingham plastic fluid past a cylinder was conducted numerically by Nirmalkar et al. [6], who reported that in the limit of plastic flow, drag approaches a constant value. Bahaduri et al. [7] developed a simple predictive tool that can be used to predict easily the boundaries of the plug of Bingham plastic fluids for laminar flow through annulus. Sayad-Ahmed et al. [8] used a numerical method to examine thermally laminar heat transfer based on the fully developed velocity for Bingham fluids in the entrance region of a circular duct. With the help of Bingham plastic model, Liu and Mei [9] made an attempt to examine the effects of wave-induced friction on a muddy sea bed. Yu et al. [10] performed a study of oscillatory flow of magnetorheological fluid dampers subject to sinusoidal displacement excitation, based on Bingham plastic and Herschel–Bulkley models.

The available scientific literature reveals that the behavior of bio-mass and some physiological fluids e.g. blood under certain pathological situations can be well described by a Bingham model. The yield stress of blood is now well established. A review of different studies on the yield stress of blood has been given in the article of Paicart et al. [11]. The Bingham plastic characteristics of blood flow through a stenosed artery was recently discussed by Yadav and Kumar [12]. Singh and Singh [13] considered the fully developed one dimensional Bingham plastic flow of blood through a small artery having multiple stenoses and post-stenotic dilation. Using regular perturbation method, the oscillatory flow of a Bingham plastic fluid was studied theoretically by De-Chant [14], who made an attempt to develop a relationship between the velocity field and dimensionless flow rate. The author mentioned that this study was motivated towards examining blood flow in arteries in a pathological state and claimed that the solution reported by him provides useful analytical models that bear the potential to support experimental and computational studies on arterial blood flow.

Several benchmark contributions have been made by Misra et al. (cf. [15–40]) to explore a variety of information in hemorheology. Since a single non-Newtonian model is inadequate to describe the complexity of blood and its flow in normal/diseased arteries, they have used different non-Newtonian models, e.g. Casson model, micropolar fluid model, power law fluid model, couple stress fluid model, viscoelastic fluid model and Herschel–Bulkley fluid model. In each case, the choice of a particular model has been made by keeping an eye on the objective of the study. Some of their studies pertain to arterial blood flow in the normal physiological state, while some others are concerned with blood flow in arteries under pathological conditions. Some of the hemorheological studies conducted by Misra et al. that have been mentioned above also involve application of transport theory in porous media.

An investigation on peristaltic motion of blood in the microcirculatory system was recently conducted by Misra and Maiti [33], in which the non-Newtonian behaviour of blood has been modelled as a Herschel–Bulkley fluid and the vessel has been considered to be of varying cross-section. In this communication, the authors mentioned that the Herschel–Bulkley fluid model is more general than most other non-Newtonian models and that the results for a fluid represented by the Bingham plastic fluid model can be derived from those of any study conducted with consideration of blood as a Herschel–Bulkley fluid.

An interesting study on the effect of thermal radiation on the magnetohydrodynamic flow of blood and heat transfer in a permeable capillary in stretching motion has been reported by Misra and Sinha [34]. In this study, the lumen of the capillary has been considered to have turned into a porous structure due to some arterial disease. The authors have developed a suitable numerical model to study the problem. The results obtained on the basis of the study have an important bearing on the therapeutic procedure of electromagnetic hyperthermia, particularly in understanding/regulating blood flow and heat transfer in capillaries.

A similar model for blood flow and vessel geometry was formulated and analyzed by Maiti and Misra [35] in their recent investigation of the non-Newtonian characteristics of peristaltic flow of blood through micro-vessels, e.g. arterioles and venules. On the

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