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Research Article

Jeffrey Fluid Flow through Porous Medium in the Presence of Magnetic Field in Narrow Tubes

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Jeffrey fluid flow in the presence of magnetic field through porous medium in tubes of small diameters is studied. It is assumed that the core region consists of a Jeffrey fluid and the peripheral region of a Newtonian fluid. Making the assumptions as in the work of Chaturani and Upadhya, the linearised equations of motion have been solved and analytical solution has been obtained. The influence of various pertinent parameters on the flow characteristics such as effective viscosity, core hematocrit, and mean hematocrit has been studied and discussed through graphs. It is found that the effective viscosity and mean hematocrit decrease with Jeffrey parameter and Darcy number but increase with tube hematocrit and tube radius. Also, the core hematocrit decreases with Jeffrey parameter, Darcy number, tube hematocrit, and tube radius. Further, it is noticed that the flow exhibits the anomalous Fahraeus-Lindquist effect.

1. Introduction

Microcirculation is a part of human circulatory system, which consists of a complex network of blood vessels, whose diameter ranges from approximately 20 μm (microns) to 500 μm. There are several types of vessels in microcirculation such as arterioles, capillaries, and venules. Its main functions are to supply oxygen and nutrients to every part of the human body. Several anomalous effects have been observed in microcirculation. In particular, the apparent viscosity of the blood increases with tube diameter and this is referred to as the Fahraeus-Lindquist effect. This effect has been confirmed by several investigators.

To explain the observed Fahraeus-Lindquist effect, Haynes [1] considered a two-fluid model with both fluids as Newtonian fluids with different viscosities. Bugliarello and Sevilla [2] have considered a two-fluid model where in the core region as well as peripheral region fluids are both Newtonian with different viscosities or both fluids are Casson's fluid with different yield coefficients and viscosities. Sharan and Popel [3] and Srivastava [4] have reported that, for blood flowing through narrow tubes, there is a peripheral layer of plasma and a core region of suspension of all erythrocytes. Following the theoretical study of Haynes [1] and experimentally tested model of Bugliarello and Sevilla [2], two-fluid modeling of blood flow has been discussed and used by a good number of researchers. Several non-Newtonian fluid models have been considered for blood flow in small diameter tubes. Chaturani and Upadhya [5, 6] analyzed two-fluid models assuming Newtonian fluid in peripheral region and micropolar and couple stress fluids in the core region. Bali and Awasthi [7] presented a mathematical model for blood flow in a small blood vessel in the presence of a magnetic field. Kumar et al. [8] investigated a computational technique for flow in blood vessels with porous effects. Gupta [9] investigated computational study of blood flow through stenosed artery with magnetic effects.

A porous medium is a material volume consisting of solid matrix with an interconnected void. Flows through a porous medium have several practical applications present in nature: flow in sand beds, in petroleum reservoir rocks, slurries, sedimentation, and so forth. Examples of natural porous media are beach sand, sandstone, limestone, the human lung, bile duct, and gall bladder with stones in small blood vessels. Flow through porous medium has been studied by a number of workers employing Darcy's law. Furthermore, the study of magnetohydrodynamics (MHD) flow problems has gained considerable interest because of its extensive engineering and medical applications. The MHD deals with the dynamics of electrically conducting fluids. Some investigators have considered the MHD studies of Newtonian and non-Newtonian fluids in different flow geometries. Misra et al. [10] have investigated a mathematical modeling of blood flow in porous vessel having double stenosis in the presence of an external magnetic field. Eldabe et al. [11] studied the peristaltic motion of non-Newtonian fluid with heat and mass transfer through a porous medium in the channel under the effect of magnetic field.

A non-Newtonian fluid model that has attracted many researchers is the Jeffrey fluid as this is found to be a better model for physiological fluids [12]. Jeffrey fluid model is a significant generalization of Newtonian fluid model as the latter one can be deduced as a special case of the former. Several researchers have studied Jeffrey fluid flows under different conditions. Ebaid et al. [13] have studied the peristaltic transport in an asymmetric channel through a porous medium. Vajravelu et al. [14] investigated the influence of heat transfer on peristaltic transport of a Jeffrey fluid. Jyothi et al. [15] have considered the pulsatile flow of a Jeffrey fluid in a circular tube lined internally with porous material. Ebaid [16] has analyzed a mathematical model to study the peristaltic transport of an incompressible viscous fluid in an asymmetric channel under the effect of transverse magnetic field with slip boundary conditions. Akbar et al. [17] have studied the Jeffrey fluid model for the peristaltic flow of chyme in the small intestine with magnetic field. Abd-Alla et al. [18] have investigated the peristaltic flow of a Jeffrey fluid in an asymmetric channel. Recently, Nallapu and Radhakrishnamacharya [19] studied a two-fluid model for the flow of Jeffrey fluid in tubes of small diameters.

In the present paper, a two-fluid model for the flow of Jeffrey fluid through a porous medium in tubes of small diameters with magnetic effect has been investigated. It is assumed that the core region consists of Jeffrey fluid and the peripheral region consists of Newtonian fluid. Making the assumptions as in the work of Chaturani et al. [6], the linearised equations of motion have been solved and analytical solution has been obtained. The influence of various pertinent parameters on the flow characteristics such as effective viscosity, core hematocrit, and mean hematocrit has been studied.

2. Formulation of the Problem

Consider an axisymmetric, laminar, steady flow of an electrically conducting Jeffrey fluid through a circular tube of radius "a" filled with porous medium. It is assumed that a uniform magnetic field B_0 is applied transversely to the flow. It is assumed that the system consists of two immiscible layers of fluids; the inside layer is non-Newtonian fluid obeying

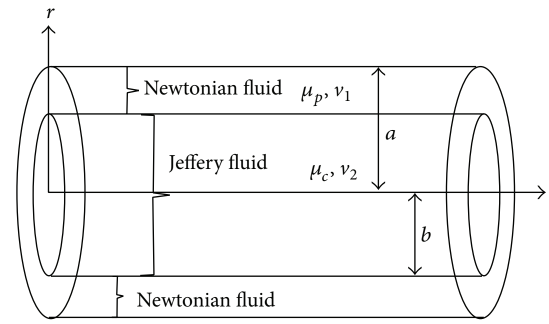

Figure 1: Flow geometry of blood in small vessels.

Jeffery model and takes cylindrical shape of radius b, while the outside layer is Newtonian fluid and takes cylindrical shape of radius a. Further, the cylinders have a common axis. It is clear that the surface of discontinuity between them is imaginary due to the two fluids being immiscible, as shown in Figure 1. Let μ_p and μ_c be the viscosities of Newtonian fluid in the peripheral region and Jeffrey fluid in the core region, respectively.

Here, $\overline{q}$ is the velocity of the fluid, $\overline{j}$ is the current density, $\overline{B} = (\overline{B}_0 + \overline{B}_1)$ is the total magnetic field, $\overline{B}_1$ is the induced magnetic field ($\overline{B}_1 \ll \overline{B}_0$), and $\overline{j} \times \overline{B}$ is Lorentz's force which is the body force acting on the fluid. The Maxwell equations and Ohm's law (on neglecting the displacement currents) are

$$\nabla \cdot \overline{B} = 0, \qquad \nabla \times \overline{B} = \mu_m \overline{j}, \qquad \nabla \times \overline{E} = -\frac{\partial \overline{B}}{\partial t}, \qquad \overline{j} = \sigma \left(\overline{E} + \overline{q} \times \overline{E} \right), \tag{1}$$

where σ is the electrical conductivity, μ_m is the magnetic permeability, and $\overline{E}$ is the electric field. The imposed and induced electric fields are assumed to be negligible. The magnetic Reynolds number is assumed to be small so that the induced magnetic field is neglected.

Hence, the force $\overline{j} \times \overline{B}$ simplifies to

$$\overline{j} \times \overline{B} = -\sigma B_0^2 w. \tag{2}$$

Cylindrical polar coordinate system (r, θ, z) is chosen, where the z-axis is taken along the axis of the tube. The equations governing the steady two-dimensional flow of an incompressible Jeffrey fluid for the present problem are as follows.

Equation of Continuity. One has

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0. \tag{3}$$

Equations of Motion. Consider

$$\rho \left[v_r \frac{\partial}{\partial r} + v_z \frac{\partial}{\partial z} \right] v_r = -\frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \overline{S}_{rr} \right) + \frac{\partial}{\partial z} \left(\overline{S}_{rz} \right) - \frac{\mu_c}{k_0} v_r,$$

$$\rho\left[v_r\frac{\partial}{\partial r}+v_z\frac{\partial}{\partial z}\right]v_z = -\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\bar{S}_{zr}\right)+\frac{\partial}{\partial z}\left(\bar{S}_{zz}\right)-\sigma B_0^2 v_z-\frac{\mu_c}{k_0}v_z, \quad (4)$$

in which

$$\begin{aligned}\bar{S}_{rr} &= \frac{2\mu_c}{1+\lambda_1}\left[1+\lambda_2\left(v_r\frac{\partial}{\partial r}+v_z\frac{\partial}{\partial z}\right)\right]\left(\frac{\partial v_r}{\partial r}\right),\\ \bar{S}_{rz} = \bar{S}_{zr} &= \frac{\mu_c}{1+\lambda_1}\left[1+\lambda_2\left(v_r\frac{\partial}{\partial r}+v_z\frac{\partial}{\partial z}\right)\right]\left(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z}\right),\\ \bar{S}_{zz} &= \frac{2\mu_c}{1+\lambda_1}\left[1+\lambda_2\left(v_r\frac{\partial}{\partial r}+v_z\frac{\partial}{\partial z}\right)\right]\frac{\partial v_z}{\partial z}\end{aligned} \quad (5)$$

are the extra stress components.

Further, v_r and v_z are the velocity components in the r- and z-directions, respectively, λ_1 is the ratio of relaxation to retardation times, λ_2 is the retardation time, p is the pressure, ρ is the density, k_0 is the permeability of the porous medium, σ is the electrical conductivity of the fluid, Da$(=k_0/a^2)$ is the Darcy number, and $M(=\sqrt{\sigma/\mu}B_0 a)$ is the magnetic parameter.

It is assumed that the flow is in the z-direction only and hence the velocity component $v_r = 0$. Consequently, the equations governing the flow of fluid (Jeffrey fluid) in the core region $(0 \le r \le b)$ reduce to

$$\begin{aligned}\frac{\partial p}{\partial r} &= 0,\\ \frac{\mu_c}{1+\lambda_1}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)-\sigma B_0^2 v_z-\frac{\mu_c}{k_0}v_z-\frac{\partial p}{\partial z} &= 0.\end{aligned} \quad (6)$$

Let $v_z(r) = v_1(r)$ be the velocity in the peripheral region and $v_2(r)$ in the core region. The equations governing the flow of fluid are as follows.

Peripheral Region (Newtonian Fluid). Consider

$$\mu_p\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_1}{\partial r}\right)-\sigma B_0^2 v_1-\frac{\mu_p}{k_0}v_1-\frac{\partial p}{\partial z}=0 \quad \text{for } b\le r\le a. \quad (7)$$

Core Region (Jeffrey Fluid). One has

$$\frac{\mu_c}{1+\lambda_1}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_2}{\partial r}\right)-\sigma B_0^2 v_2-\frac{\mu_c}{k_0}v_2-\frac{\partial p}{\partial z}=0 \quad \text{for } 0\le r\le b, \quad (8)$$

where $\partial p/\partial z$ is the constant pressure gradient.

The boundary conditions for the problem are given by

$$v_1 = 0, \quad \text{at } r = a, \quad (9a)$$

$$v_1 = v_2, \qquad \tau_1 = \tau_2, \quad \text{at } r = b, \quad (9b)$$

$$v_2 \text{ is finite} \quad \text{at } r = 0. \quad (9c)$$

Condition (9a) is the classical no-slip boundary condition for the velocity; (9b) denotes the continuity of velocities and stresses at the interface and (9c) is the regularity condition.

Solving (7) and (8) under conditions (9a), (9b), and (9c), we get

$$v_1(\xi) = \frac{a^2P}{\mu_p\alpha}\left(1-\frac{I_0(\sqrt{\alpha}\cdot\xi)}{I_0(\sqrt{\alpha})}\right) \quad \text{for } d\le\xi\le 1, \quad (10)$$

$$v_2(\xi) = \frac{a^2P}{\mu_p\alpha}\left(1-\frac{I_0(\sqrt{\alpha}\cdot d)}{I_0(\sqrt{\alpha})}+\mu'\beta\left[1-\frac{I_0(\omega\cdot\xi)}{I_0(\omega d)}\right]\right) \quad \text{for } 0\le\xi\le d, \quad (11)$$

where

$$\begin{aligned}&\xi=\frac{r}{a}, \qquad d=\frac{b}{a}, \qquad P=-\frac{\partial p}{\partial z},\\ &\mu'=\frac{\mu_p}{\mu_c}, \qquad \alpha=M_p^2+\frac{1}{\text{Da}},\\ &\beta=\frac{\alpha}{M_c^2+(1/\text{Da})},\\ &\omega=\sqrt{(1+\lambda_1)\left(M_c^2+\frac{1}{\text{Da}}\right)}.\end{aligned} \quad (12)$$

The flow flux in the peripheral region, denoted by Q_p, is defined by

$$Q_p = 2\pi a^2\int_d^1 v_1(\xi)\,\xi d\xi. \quad (13)$$

Substituting for $v_1(\xi)$ from (10) in (13), we get

$$Q_p = \frac{a^4P\pi}{\mu_p\alpha}\left(1-d^2+2\frac{dI_1(\sqrt{\alpha}\cdot d)-I_1(\sqrt{\alpha})}{\sqrt{\alpha}I_0(\sqrt{\alpha})}\right). \quad (14)$$

Similarly, the flow flux in the core region is given by

$$\begin{aligned}Q_c &= 2\pi a^2\int_0^d v_2(\xi)\,\xi d\xi\\ &= \frac{a^4P\pi}{\mu_p\alpha}\left(d^2-d^2\frac{I_0(\sqrt{\alpha}\cdot d)}{I_0(\sqrt{\alpha})}+\mu'\beta\left[d^2-2d\frac{I_1(\omega d)}{\omega I_0(\omega d)}\right]\right).\end{aligned} \quad (15)$$

Thus, the flow flux through the tube is given by

$$Q = Q_p + Q_c. \quad (16)$$

Using (14) and (15) in (16), we get

$$\begin{aligned}Q = \frac{a^4P\pi}{\mu_p\alpha}\Bigg(&1+2\frac{dI_1(\sqrt{\alpha}\cdot d)-I_1(\sqrt{\alpha})}{\sqrt{\alpha}I_0(\sqrt{\alpha})}-d^2\frac{I_0(\sqrt{\alpha}\cdot d)}{I_0(\sqrt{\alpha})}\\ &+\mu'\beta\left[d^2-2d\frac{I_1(\omega d)}{\omega I_0(\omega d)}\right]\Bigg).\end{aligned} \quad (17)$$

Comparing (17) with flow flux for Poiseuille flow, we get the effective viscosity as follows:

$$\mu_{\text{eff}} = \mu_p \alpha \times \left(8\text{Da} \left(1 + 2\frac{dI_1(\sqrt{\alpha} \cdot d) - I_1(\sqrt{\alpha})}{\sqrt{\alpha} I_0(\sqrt{\alpha})} - d^2 \frac{I_0(\sqrt{\alpha} \cdot d)}{I_0(\sqrt{\alpha})} + \mu' \beta \left[d^2 - 2d\frac{I_1(\omega d)}{\omega I_0(\omega d)} \right] \right) \right)^{-1}. \quad (18)$$

2.1. Mean Hematocrit for Cell-Free Wall Layer. The percentage volume of red blood cells is called the hematocrit and is approximately 40–45% for human adults.

The core hematocrit H_c is related to the hematocrit H_0 of blood leaving or entering the tube by

$$H_0 Q = H_c Q_c. \quad (19)$$

Substituting for Q_c and Q from (15) and (17) in (19), we get (after simplification)

$$\overline{H}_c = \frac{H_c}{H_0} = 1 + \left(1 - d^2 + 2\frac{dI_1(\sqrt{\alpha} \cdot d) - I_1(\sqrt{\alpha})}{\sqrt{\alpha} I_0(\sqrt{\alpha})} \times \left(d^2 - d^2 \frac{I_0(\sqrt{\alpha} \cdot d)}{I_0(\sqrt{\alpha})} + \mu' \beta \left[d^2 - 2d\frac{I_1(\omega d)}{\omega I_0(\omega d)} \right] \right)^{-1} \right), \quad (20)$$

where $\overline{H}_c$ is the normalized core hematocrit.

The mean hematocrit within the tube H_m is related to the core hematocrit H_c by

$$H_m \pi a^2 = H_c \pi b^2. \quad (21)$$

On simplification, we get

$$\overline{H}_m = \frac{H_m}{H_0} = \frac{H_c}{H_0} d^2 = \overline{H}_c d^2, \quad (22)$$

where $\overline{H}_m$ is the normalized mean hematocrit.

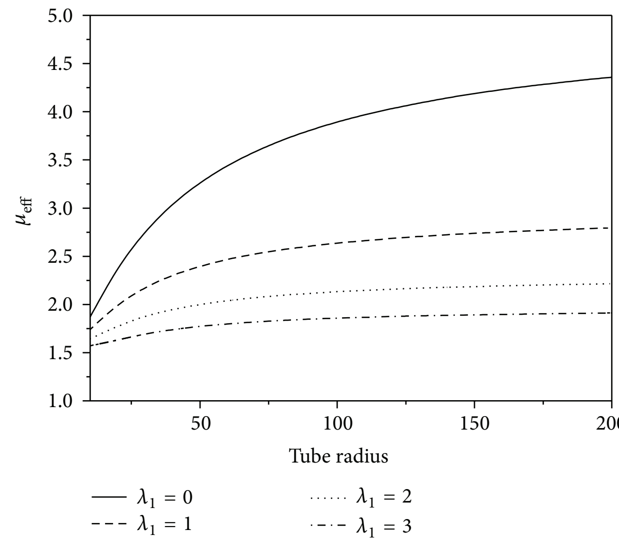

Figure 2: Effect of λ_1 on μ_{eff} ($H_0 = 40\%$, $M_p = 1$, $M_c = 0.5$, and Da = 0.5).

Substituting for $\overline{H}_c$ from (20) in (22), we get

$$\overline{H}_m = \frac{H_m}{H_0} = \frac{H_c}{H_0} d^2 = \left(1 + \left(1 - d^2 + 2\frac{dI_1(\sqrt{\alpha} \cdot d) - I_1(\sqrt{\alpha})}{\sqrt{\alpha} I_0(\sqrt{\alpha})} \times \left(d^2 - d^2 \frac{I_0(\sqrt{\alpha} \cdot d)}{I_0(\sqrt{\alpha})} + \mu' \beta \left[d^2 - 2d\frac{I_1(\omega d)}{\omega I_0(\omega d)} \right] \right)^{-1} \right) \right) d^2. \quad (23)$$

3. Results and Discussion

In order to discuss the effects of Jeffrey parameter (λ_1), core magnetic parameter (M_c), Darcy number (Da), tube hematocrit (H_0), and tube radius (a) on effective viscosity μ_{eff}, core hematocrit $\overline{H}_c$, and mean hematocrit $\overline{H}_m$, they have been numerically computed and graphically presented in Figures 2–13. In the present analysis, the values of μ_p are taken as 1.2 μm, $\mu_c = 4.0$ μm and the value of d is calculated from the relation $d = 1 - (\epsilon/a)$ in which $\epsilon = 3.12$ μm for 40% hematocrit, 3.60 μm for 30%, and 4.67 μm for 20% [5].

Figures 2–5 show the variation of effective viscosity (μ_{eff}) for different values of Jeffrey parameter λ_1, core magnetic parameter (M_c), Darcy number (Da), tube hematocrit (H_0), and tube radius (a). It can be seen that the effective viscosity decreases with Jeffrey parameter (λ_1) (Figure 2) and Darcy number (Da) (Figure 3) but increases with core magnetic parameter (M_c) (Figure 4) and tube hematocrit H_0 (Figure 5). These results are in agreement with the results of Bugliarello and Sevilla [2], Srivastava [4], and Chaturani and Upadhya

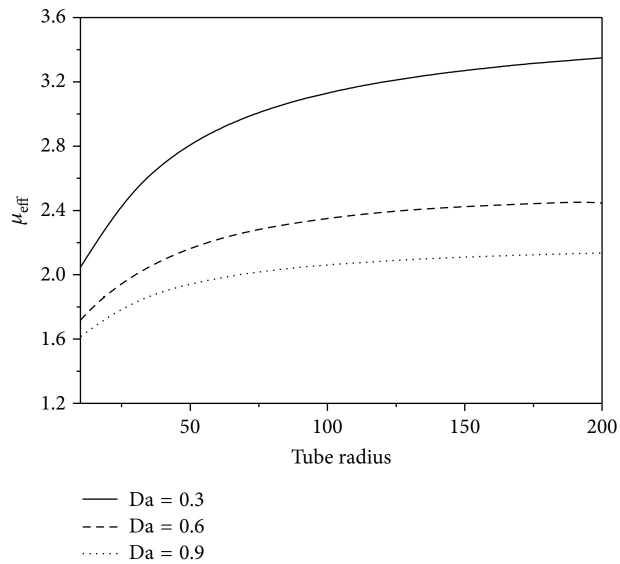

FIGURE 3: Effect of Da on μ_{eff} (H_0 = 40%, λ_1 = 2, M_p = 1, and M_c = 0.5).

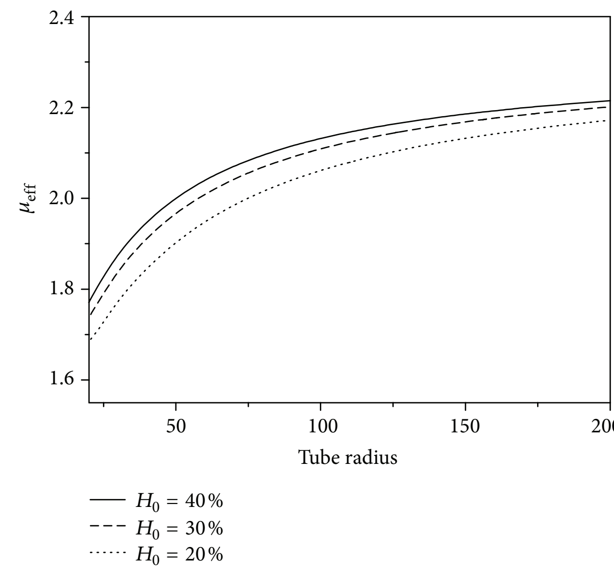

FIGURE 5: Effect of H_0 on μ_{eff} (λ_1 = 2, M_p = 1, M_c = 0.5, and Da = 0.5).

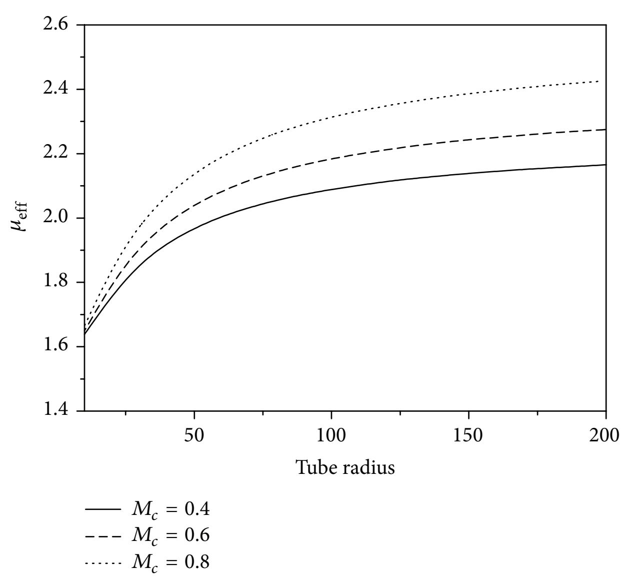

FIGURE 4: Effect of M_c on μ_{eff} (H_0 = 40%, λ_1 = 2, M_p = 1, and Da = 0.5).

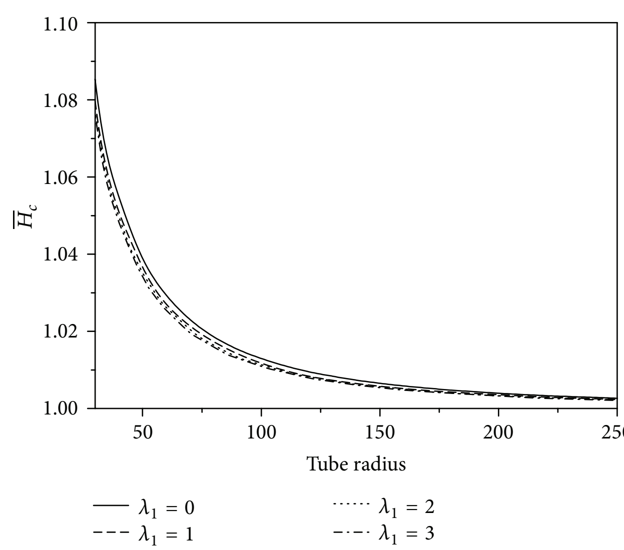

FIGURE 6: Effect of λ_1 on $\overline{H}_c$ (H_0 = 40%, M_p = 1, M_c = 0.5, and Da = 0.5).

[5]. Further, for given values of all the parameters, the effective viscosity (μ_{eff}) increases with tube radius (a); that is, the flow exhibits the Fahraeus-Lindquist effect. For higher values of Jeffrey parameter (λ_1) and Darcy number (Da), the increase in effective viscosity with tube radius is not very significant for values of tube radius larger than 75 μm (Figures 2 and 3).

The effects of Jeffrey parameter (λ_1), core magnetic parameter (M_c), Darcy number (Da), tube hematocrit (H_0), and tube radius (a) on core hematocrit ($\overline{H}_c$) and mean hematocrit ($\overline{H}_m$) are depicted in Figures 6–13. It can be seen that the core hematocrit ($\overline{H}_c$) decreases with Jeffrey parameter (λ_1) (Figure 6), Darcy number (Da) (Figure 7), tube hematocrit (H_0) (Figure 8), and tube radius "a." It can be observed that core hematocrit ($\overline{H}_c$) decreases with tube radius (Figures 6–9). Figure 9 shows that the influence of magnetic parameter (M_c) on core hematocrit is very insignificant. Also, the mean hematocrit ($\overline{H}_m$) decreases with Jeffrey parameter (λ_1) (Figure 10) and Darcy number (Da) (Figure 11) but increases with tube hematocrit (H_0) (Figure 12) and tube radius "a." It can be observed that mean hematocrit ($\overline{H}_m$) increases with tube radius (Figures 10–13). The influence of magnetic parameter (M_c) on mean hematocrit ($\overline{H}_m$) is very insignificant (Figure 13).

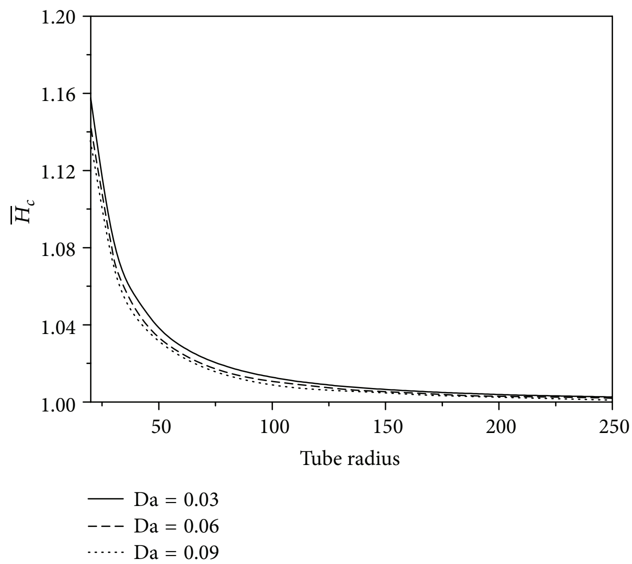

Figure 7: Effect of Da on $\overline{H}_c$ (H_0 = 40%, λ_1= 2, M_p = 1, and M_c = 0.5).

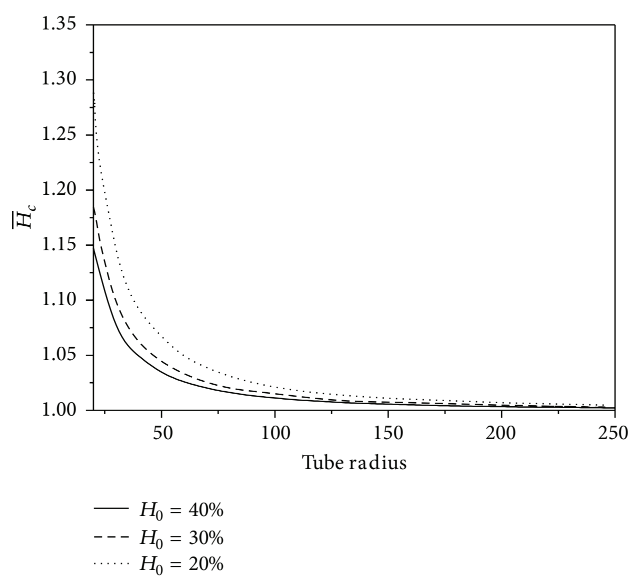

Figure 8: Effect of H_0 on $\overline{H}_c$ (λ_1 = 2, M_p = 1, M_c = 0.5, and Da = 0.5).

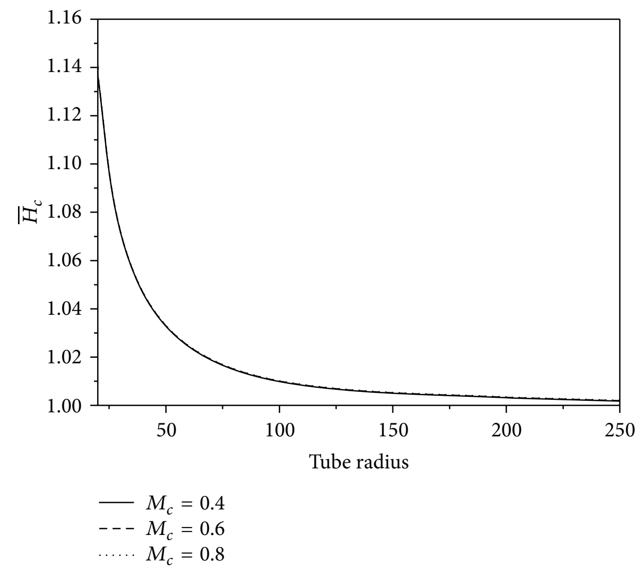

Figure 9: Effect of M_c on $\overline{H}_c$ (H_0 = 40%, M_p = 1, λ_1 = 2, and Da = 0.5).

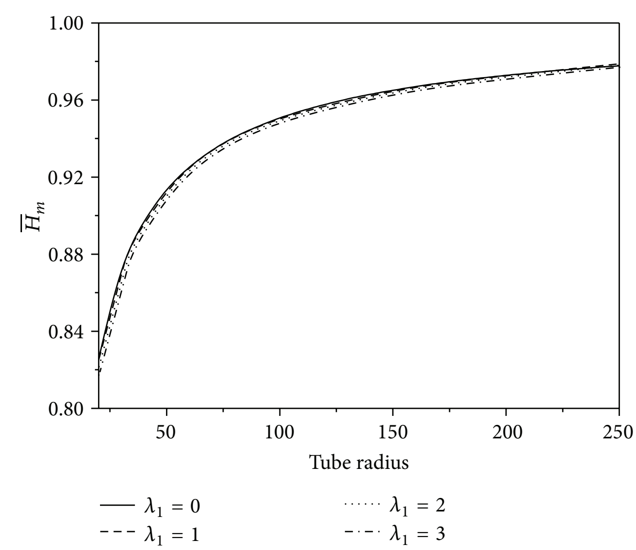

Figure 10: Effect of λ_1 on $\overline{H}_m$ (H_0 = 40%, M_p = 1, M_c = 0.5, and Da = 0.5).

4. Conclusions

A two-fluid model has been proposed to describe flow through porous medium in small diameter tubes with Jeffrey fluid in the core region and Newtonian fluid in the peripheral region in the presence of a magnetic field. It is found that the effective viscosity increases with Jeffrey parameter, core magnetic parameter, Darcy number, tube hematocrit, and tube radius. Further, the core hematocrit decreases with Jeffrey parameter, Darcy number, tube hematocrit, and tube radius and the mean hematocrit increases with Jeffrey parameter, Darcy number, tube hematocrit, and tube radius. The influence of magnetic parameter on core hematocrit and mean hematocrit is very insignificant.

Nomenclature

a: Tube radius
b: Radius of the core region
d: Dimensionless core radius = $1 - (\epsilon/a)$
ϵ: Peripheral region thickness = $a - b$
ξ: Dimensionless radial direction r/a
μ': Ratio of viscosity = μ_p/μ_c
μ_p: Peripheral region viscosity

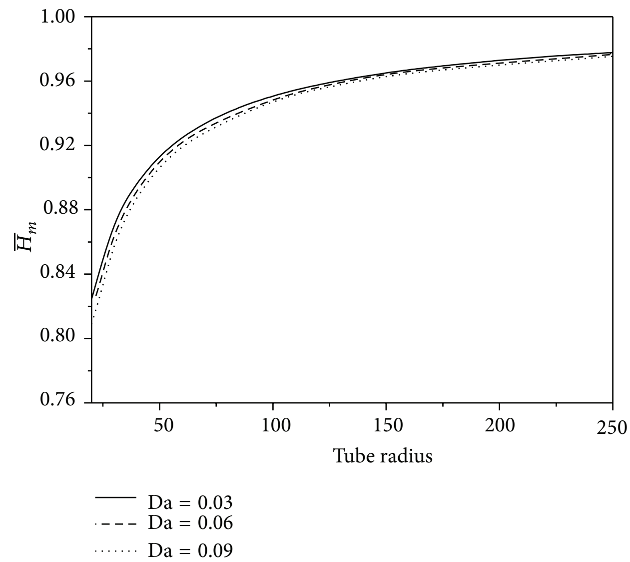

Figure 11: Effect of Da on $\overline{H}_m$ ($H_0 = 40\%$, $\lambda_1 = 2$, $M_p = 1$, and $M_c = 0.5$).

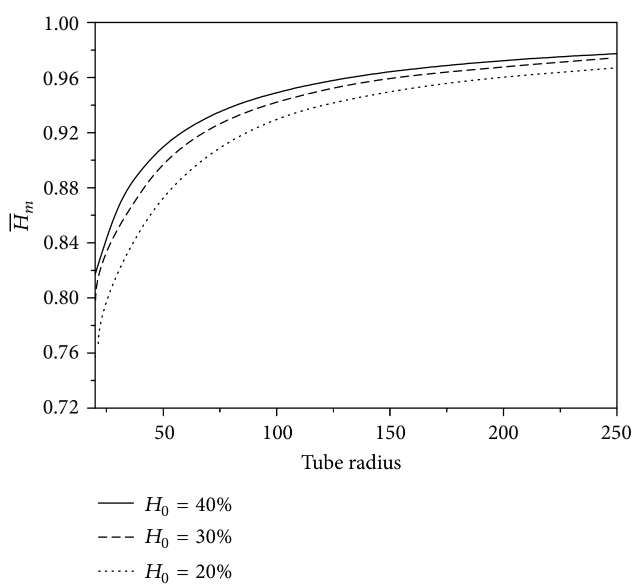

Figure 12: Effect of H_0 on $\overline{H}_m$ ($\lambda_1 = 2$, $M_p = 1$, $M_c = 0.5$, and Da = 0.5).

λ_1: Jeffrey parameter
Da: Darcy number = k_0/a^2
σ: Electrical conductivity
M_p: Magnetic parameter in peripheral region = $\sqrt{\sigma/\mu_p}B_0 a$
M_c: Magnetic parameter in core region = $\sqrt{\sigma/\mu_c}B_0 a$
r: Radial direction
z: Axial direction
v_1: Velocity in peripheral region
v_2: Velocity in core region
p: Pressure

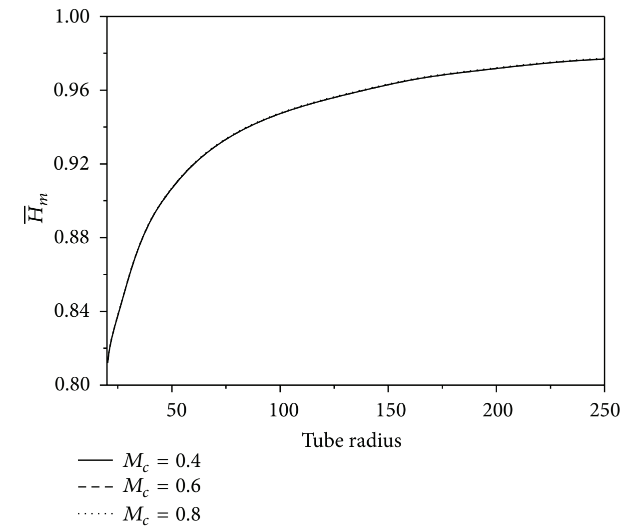

Figure 13: Effect of M_c on $\overline{H}_m$ ($H_0 = 40\%$, $M_p = 1$, $\lambda_1 = 2$, and Da = 0.5).

P: Constant pressure gradient = $-(\partial p/\partial z)$
μ_c: Core region viscosity
ρ: Density
k_0: Permeability of porous medium
B_0: Uniform magnetic field.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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