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Effects of Joule heating, thermal radiation on MHD pulsating flow of a couple stress hybrid nanofluid in a permeable channel

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Abstract: The current work deals with the pulsatile hydromagnetic flow of blood-based couple stress hybrid nanofluid in a porous channel. For hybrid nanofluid, the fusion of gold (Au) and copper oxide (CuO) nanoparticles are suspended to the blood (base fluid). In this model, the employment of viscous dissipation, radiative heat, and Ohmic heating is incorporated. The governing flow equations (set of partial differential equations) are modernized to set of ordinary differential equations by using the perturbation technique. The nondimensional governing equations are solved by adopting the shooting procedure with the help of the Runge–Kutta fourth-order approach. Temperature distributions of hybrid nanofluid and conventional mono nanofluids are portrayed via pictorial results to claim that the hybrid nanofluid has better temperature distribution than mono nanofluids. Temperature is raising for the magnifying viscous dissipation, whereas the reverse behavior can be found with a rise in couple stress parameter. The heat transfer rate is getting high for the higher values of the Eckert number, and the same behavior is noticed with the uplifting magnetic field.

Keywords: pulsatile flow, porous channel, couple stress hybrid nanofluid, Joule heating, thermal radiation.

1 Introduction

The thermal conductivity of nanoparticles helped to enhance the lower thermal conductivity of base fluids, which is named as nanofluids addressed by Choi and Eastman [4]. These innovative heat transfer fluids have enormous thermal absorption/eviction applications in industries as well as day-to-day life [3, 8, 19]. Hatami et al. [9] studied the flow of a non-Newtonian blood-gold nanofluid in a permeable channel with the presence of magnetic effect by utilizing numerical and analytical investigations. Exclamatory outcomes in heat transfer demands and the outlandish behavior of nanofluids accelerate us to the next generation of nanofluids, by fusing more than one dissimilar nanoparticles in a base fluid, to get the additive effects of those nanoparticles for the enrichment in heat transfer of base fluids, this next step of nanofluids is known as hybrid nanofluids. Hybrid nanofluids are planned to further

enhancement in heat transfer than mono nanofluids such as overcoming the defectivity of heat transfer in certain situations of conventional ones and improve the heat transfer rate in applications of single nanoparticle suspended base fluid [20, 22]. Devi and Devi [7] numerically studied the course of a hybrid nanofluid over an expanding sheet with the upshots of suction and magnetic parameters. Hussain et al. [10] inspected the flow of a hydromagnetic hybrid nanofluid in an open cavity with a horizontal channel by employing various numerical techniques. Ahmed and Xu [2] analytically examined the unsteady pulsating flow of copper-alumina-water hybrid nanofluid driven in a microchannel with the consideration of magnetic parameter and thermal radiation effects. Muneeshwaran et al. [14] done a review on the role of hybrid nanofluid on thermal transport phenomenon. Here the authors claimed that the thermal conductivity of hybrid nanofluid is the reason behind for the increment in heat transfer rate, and the thermophysical properties are the main factors that affect the stability of hybrid nanoparticles.

To understand the flow behavior of many real-life fluids taken part in calamity situations and vast industrial applications, the knowledge of non-Newtonian fluids is mattered to us. Couple stress fluids are the desirable kind of non-Newtonian fluids due to their help to get the schematic blueprint of the flow behavior of biofluids such as blood, synovial fluid [6, 26]. The motif of couple stress theory proposed by Stokes [27] by modeling the mechanical interactions of fluid particles on the root of continuum concept. Adesanya and Makinde [1] analyzed the pressure-driven flow of a couple stress fluid with the employment of magnetic parameter and thermal radiation by utilizing the Adomian decomposition method. Tripathi et al. [28] modeled the flow of couple stress hybrid nanofluid and claimed that their model is dedicated to drug delivery and smart-peristaltic mechanisms. Rajamani and Reddy [17] analytically studied the magnetohydrodynamic pulsatile flow of a couple stress nanofluid via channel with the presence of Joule heating and radiative heat by using the perturbation technique. Here the authors validated their results with the comparison of outcomes from perturbation technique and Runge–Kutta 4th order scheme with the support of shooting technique. Recently, Jawad et al. [11] have carried out an analytical investigation for the couple stress hybrid nanofluid flow past a permeable sheet with the presence of magnetic field, Brownian motion, thermophoresis, heat source, and thermal radiation. Here the authors considered the couple stress hybrid nanoparticles as a targeted drug carrier that can be utilized in the biomedicine fields in the drug delivery system.

In the light of promising benefits in engineering and industries, like power generation, space devices, polymer processing, electrical and electronic devices [5, 25], there is a lot to discuss about Joule heating, thermal radiation, and viscous dissipation effects. Zaib and Shafie [33] investigated the unsteady flow of electrically treated fluid past an expanding sheet with the episodes of thermal radiation, viscous dissipation, and Joule heating. Kumar et al. [13] studied the pulsating flow of MHD Casson nanofluid in a vertical permeable space. Here the impacts of

Ohmic and viscous dissipations are taken into account. An inspection for the radiative heat on the flow of non-Newtonian fluid in a penetrable medium with effects of heat source/sink and the magnetic parameter was done by Khedr et al. [12]. Sreedevi et al. [24] analyzed the thermal radiation for the unsteady hybrid nanofluid flow with the effects of magnetic and suction parameters.

In this study, a numerical study of MHD pulsatile flow of electrically treated couple stress hybrid nanofluid in a penetrable channel with the influences of Joule heating and thermal radiation is inspected. Hybrid nanoparticles are the fusion of gold and copper oxide nanoparticles. Blood is considered as the electrically conducting base fluid due to influencing applications not only in the bio-medical field but also in industries. The dynamics of blood flow is analyzed for hybrid nanofluid and the conventional mono nanofluids with the variations of emerging parameters that are involved in the current analysis. There is an enhancement in temperature distribution and the rate of heat transfer while using hybrid nanofluid than the mono nanofluids, which is presented via pictorial results.

2 Formulation of the problem

Consider an electrically conducting pulsating flow of a couple stress hybrid nanofluid in a permeable channel. In this study, for hybrid nanofluid, the fusion of gold and copper oxide nanoparticles are taken as nanoparticles, and the blood is chosen as base fluid. The clouts of thermal radiation, viscous dissipation, and Ohmic heating are considered into account.

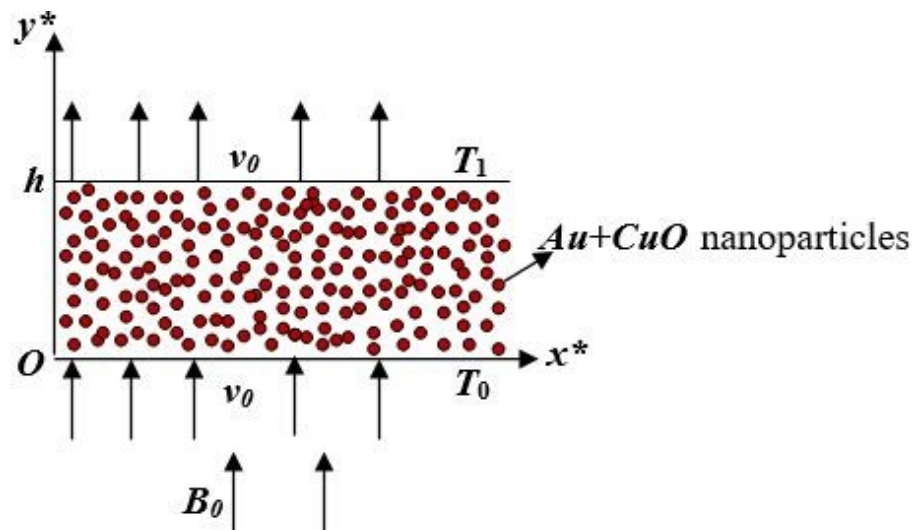


Figure 1
Flow model of the problem

Figure 1. Flow model of the problem.

The flow model of the current study is presented in Fig. 1. Let us assume that the bottom wall coincides with the is normal to it. An applied

magnetic field of magnitude B_0 is entreated uniformly orthogonal to both walls. T_1 and T_0 are the wall temperatures of upper and lower walls, respectively ($T_0 < T_1$), and d is the distance between the walls. The fluid is injected through the bottom wall with a velocity v_0 and sucked out from the top wall at the same rate. The constitutive equations concerning the force stress t_{ij} and the rate of deformation tensor d_{ij} are given by [6, 27]

$$t_{ij} = -p\delta_{ij} + \lambda \operatorname{div}(\bar{q})\delta_{ij} + 2\mu d_{ij} - \frac{1}{2}\varepsilon_{ijk}[m_k + 4\eta\omega_{k,rr} + \rho c_k],$$

$$m_{ij} = \frac{1}{3}m\delta_{ij} + 4\eta\omega_{j,i} + 4\eta'\omega_{i,j}.$$

The couple stress tensor m_{ij} that arises in the theory has the linear constitutive relation. In the above, m is the spin tensor, η is the body couple vector. These material constants are constrained by the inequalities

$$\mu \geq 0, \quad 3\lambda + 2\mu \geq 0, \quad \eta \geq 0, \quad |\eta'| \leq \eta.$$

Assume that the flow is induced by a pressure gradient, which is taken by [16, 31]

$$-\frac{1}{\rho_f} \frac{\partial P^*}{\partial x^*} = A(1 + \varepsilon e^{i\omega t^*}), \quad (1)$$

here A is a positive quantity. Under these hypotheses the governing equations of the current flow are

$$\rho_{hnf} \left[\frac{\partial u^*}{\partial t^*} + v_0 \frac{\partial u^*}{\partial y^*} \right] = -\frac{\partial P^*}{\partial x^*} + \mu_{hnf} \left(\frac{\partial^2 u^*}{\partial y^{*2}} \right) - \eta \frac{\partial^4 u^*}{\partial y^{*4}} - \sigma_{hnf} B_0^2 u^*,$$

$$(\rho C_p)_{hnf} \left[\frac{\partial T^*}{\partial t^*} + v_0 \frac{\partial T^*}{\partial y^*} \right] = k_{hnf} \frac{\partial^2 T^*}{\partial y^{*2}} + \mu_{hnf} \left(\frac{\partial u^*}{\partial y^*} \right)^2 + \eta \left(\frac{\partial^2 u^*}{\partial y^{*2}} \right)^2 \quad (2)$$

$$-\frac{\partial q_r^*}{\partial y^*} + Q_0(T^* - T_0) + \sigma_{hnf} B_0^2 u^{*2}.$$

(3)

Here u^* is the velocity along the x^* -direction, ρ represent density, μ dynamic viscosity, C_p effective specific heat, k thermal conductivity, and σ electrical conductivity of hybrid nanofluid, respectively, and the subscripts hnf and s denote hybrid nanofluid, nanofluid, base fluid (blood), and solid

nanoparticles, respectively. T^* is the temperature of hybrid nanofluid, μ is coefficient of couple stress viscosity, σ is coefficient of heat source/sink, and the radiative heat flux is denoted as q_r .

The related boundary conditions (BCs) are

$$\begin{aligned} u^*(0) &= 0, & \frac{\partial^2 u^*}{\partial y^{*2}}(0) &= 0, & T^*(0) &= T_0, \\ u^*(h) &= 0, & \frac{\partial^2 u^*}{\partial y^{*2}}(h) &= 0, & T^*(h) &= T_1. \end{aligned}$$

The thermal characteristics of blood, Au and CuO nanoparticles are specified in Table 1. The physical features of nanofluid and hybrid nanofluid are defined as [7, 10, 22]

$$\begin{aligned} (\rho C p)_{nf} &= (1 - \phi)(\rho C p)_f + \phi(\rho C p)_s, \\ \mu_{nf} &= \frac{\mu_f}{(1 - \phi)^{2.5}}, & \rho_{nf} &= (1 - \phi)\rho_f + \phi\rho_s, \\ \frac{k_{nf}}{k_f} &= \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + \phi(k_f - k_s)}, & \frac{\sigma_{nf}}{\sigma_f} &= 1 + \frac{3(\frac{\sigma_s}{\sigma_f} - \phi)}{(\frac{\sigma_s}{\sigma_f} + 2) - (\frac{\sigma_s}{\sigma_f} - 1)\phi}, \\ (\rho C p)_{hnf} &= (1 - \phi)(\rho C p)_f + \phi_{Au}(\rho C p)_{Au} + \phi_{CuO}(\rho C p)_{CuO}, \\ \mu_{hnf} &= \frac{\mu_f}{(1 - (\phi_{Au} + \phi_{CuO}))^{2.5}}, & \rho_{hnf} &= (1 - \phi)\rho_f + \phi_{Au}\rho_{Au} + \phi_{CuO}\rho_{CuO}, \\ \frac{k_{hnf}}{k_f} &= \frac{(\frac{\phi_{Au}k_{Au} + \phi_{CuO}k_{CuO}}{\phi}) + 2k_f + 2(\phi_{Au}k_{Au} + \phi_{CuO}k_{CuO}) - 2\phi k_f}{(\frac{\phi_{Au}k_{Au} + \phi_{CuO}k_{CuO}}{\phi}) + 2k_f - (\phi_{Au}k_{Au} + \phi_{CuO}k_{CuO}) + \phi k_f}, \\ \frac{\sigma_{hnf}}{\sigma_f} &= 1 + \frac{3(\frac{\phi_{Au}\sigma_{Au} + \phi_{CuO}\sigma_{CuO}}{\phi} - \phi)}{(\frac{\phi_{Au}\sigma_{Au} + \phi_{CuO}\sigma_{CuO}}{\phi} + 2) - (\frac{\phi_{Au}\sigma_{Au} + \phi_{CuO}\sigma_{CuO}}{\phi} - \phi)}. \end{aligned}$$

Here ϕ is the volume fraction of nanoparticles.

By adopting the Rosseland approximation for the radiative heat flux, Eq. (3) becomes

$$\begin{aligned} (\rho C p)_{hnf} \left[\frac{\partial T^*}{\partial t^*} + v_0 \frac{\partial T^*}{\partial y^*} \right] &= k_{hnf} \frac{\partial^2 T^*}{\partial y^{*2}} + \mu_{hnf} \left(\frac{\partial u^*}{\partial y^*} \right)^2 + \eta \left(\frac{\partial^2 u^*}{\partial y^{*2}} \right)^2 \\ &+ \frac{16}{3} \frac{\sigma^* T_1^3}{k^*} \frac{\partial^2 T^*}{\partial y^{*2}} + Q_0(T^* - T_0) + \sigma_{hnf} B_0^2 u^{*2}. \end{aligned}$$

Here η is the Rosseland mean absorption coefficient, and B_0 is the Stephen–Boltzmann constant.

Table 1

Table 1. The thermophysical properties of nanoparticles and blood [3, 19].

Property	Au	CuO	Blood
$\sigma [(\Omega \text{ m})^{-1}]$	$4.10 \cdot 10^7$	$2.7 \cdot 10^{-8}$	0.8
$\rho [\text{kg/m}^3]$	19282	6500	1050
$k [\text{W/mK}]$	310	18	0.52
$C_p [\text{J/kg K}]$	129	540	3617

Now, with the help of the ensuing nondimensional parameters,

$$\begin{aligned}
 x^* &= xh, & y^* &= yh, & t^* &= \frac{t}{\omega}, & u^* &= \frac{Au}{\omega}, \\
 P^* &= \rho_f P Ah, & T^* &= T_0 + \theta(T_1 - T_0), \\
 H &= \frac{\sqrt{\omega}h}{\sqrt{v_f}}, & M &= B_0 h \sqrt{\frac{\sigma_f}{\mu_f}}, & Pr &= \frac{v_f(\rho C_p)_f}{k_f}, & Ec &= \frac{A^2}{\omega^2(C_p)_f(T_1 - T_0)}, \\
 R &= \frac{v_0 h}{v_f}, & Rd &= \frac{4\sigma^* T_1^3}{k^* k_f}, & \lambda &= \frac{\eta}{\mu_f h^2}, & Q &= \frac{Q_0 h^2}{v_f(\rho C_p)_f}.
 \end{aligned}$$

Equations (1), (2), and (4) become

$$-\frac{\partial P}{\partial x} = 1 + \varepsilon e^{it}, \quad (5)$$

$$A_1 \left[\frac{\partial u}{\partial t} + \frac{R}{H^2} \frac{\partial u}{\partial y} \right] = -\frac{\partial P}{\partial x} + \frac{A_2}{H^2} \left(\frac{\partial^2 u}{\partial y^2} \right) - \frac{\lambda}{H^2} \frac{\partial^4 u}{\partial y^4} - \frac{A_5 M^2}{H^2} u, \quad (6)$$

$$\begin{aligned}
 A_3 \left[\frac{\partial \theta}{\partial t} + \frac{R}{H^2} \frac{\partial \theta}{\partial y} \right] &= \frac{(A_4 + \frac{4}{3} Rd)}{Pr H^2} \left(\frac{\partial^2 \theta}{\partial y^2} \right) + \frac{A_2 Ec}{H^2} \left(\frac{\partial u}{\partial y} \right)^2 + \frac{\lambda Ec}{H^2} \left(\frac{\partial^2 u}{\partial y^2} \right)^2 \\
 &+ \frac{A_5 Ec M^2}{H^2} u^2 + \frac{Q}{H^2} \theta.
 \end{aligned} \quad (7)$$

Here

$$\begin{aligned}
 A_1 &= (1 - \phi) + \phi_{\text{Au}} \frac{\rho_{\text{Au}}}{\rho_f} + \phi_{\text{CuO}} \frac{\rho_{\text{CuO}}}{\rho_f}, & A_2 &= \frac{1}{(1 - (\phi_{\text{Au}} + \phi_{\text{CuO}}))^{2.5}}, \\
 A_3 &= (1 - \phi) + \phi_{\text{Au}} \frac{(\rho C p)_{\text{Au}}}{(\rho C p)_f} + \phi_{\text{CuO}} \frac{(\rho C p)_{\text{CuO}}}{(\rho C p)_f}, \\
 A_4 &= \frac{(\frac{\phi_{\text{Au}} k_{\text{Au}} + \phi_{\text{CuO}} k_{\text{CuO}}}{\phi}) + 2k_f + 2(\phi_{\text{Au}} k_{\text{Au}} + \phi_{\text{CuO}} k_{\text{CuO}}) - 2\phi k_f}{(\frac{\phi_{\text{Au}} k_{\text{Au}} + \phi_{\text{CuO}} k_{\text{CuO}}}{\phi}) + 2k_f - (\phi_{\text{Au}} k_{\text{Au}} + \phi_{\text{CuO}} k_{\text{CuO}}) + \phi k_f}, \\
 A_5 &= 1 + \frac{3(\frac{\phi_{\text{Au}} \sigma_{\text{Au}} + \phi_{\text{CuO}} \sigma_{\text{CuO}}}{\sigma_f} - \phi)}{(\frac{\phi_{\text{Au}} \sigma_{\text{Au}} + \phi_{\text{CuO}} \sigma_{\text{CuO}}}{\sigma_f} + 2) - (\frac{\phi_{\text{Au}} \sigma_{\text{Au}} + \phi_{\text{CuO}} \sigma_{\text{CuO}}}{\sigma_f} - \phi)},
 \end{aligned}$$

where Ec is Eckert number, M is Hartmann number, Pr is Prandtl number, Q is heat source/sink parameter, H is frequency parameter, R is couple stress parameter, Rd is the radiation parameter.

The corresponding BCs are

$$\begin{aligned}
 u(0) &= 0, & \frac{\partial^2 u}{\partial y^2}(0) &= 0, & \theta(0) &= 0, \\
 u(1) &= 0, & \frac{\partial^2 u}{\partial y^2}(1) &= 0, & \theta(1) &= 1.
 \end{aligned}$$

Solution of the problem

to Eq. (5), the solution locutions for can be taken as

$$u(y) = u_0(y) + \varepsilon u_1(y)e^{it}, \quad (8)$$

$$\theta(y) = \theta_0(y) + \varepsilon \theta_1(y)e^{it}. \quad (9)$$

By substituting Eqs. (5), (8) and (9) into the Eqs. (6)–(7) and then likening the coefficients of different powers of ε , one can get

$$\lambda \frac{d^4 u_0}{dy^4} - A_2 \frac{d^2 u_0}{dy^2} + A_1 R \frac{du_0}{dy} + A_5 M^2 u_0 = H^2, \quad (10)$$

$$\lambda \frac{d^4 u_1}{dy^4} - A_2 \frac{d^2 u_1}{dy^2} + A_1 R \frac{du_1}{dy} + (iA_1 H^2 + A_5 M^2) u_1 = H^2,$$

$$\begin{aligned} & \frac{1}{Pr} \left(A_4 + \frac{4}{3} Rd \right) \frac{d^2 \theta_0}{dy^2} - A_3 R \frac{d\theta_0}{dy} + Q\theta_0 + \lambda Ec \left(\frac{d^2 u_0}{dy^2} \right)^2 + A_2 Ec \left(\frac{du_0}{dy} \right)^2 \\ & + A_5 Ec M^2 u_0^2 = 0, \\ & \frac{1}{Pr} \left(A_4 + \frac{4}{3} Rd \right) \frac{d^2 \theta_1}{dy^2} - A_3 R \frac{d\theta_1}{dy} + (Q - iA_3 H^2) \theta_1 + 2\lambda Ec \frac{d^2 u_0}{dy^2} \frac{d^2 u_1}{dy^2} \\ & + 2A_2 Ec \frac{du_0}{dy} \frac{du_1}{dy} + 2A_5 Ec M^2 u_0 u_1 = 0. \end{aligned} \quad (13)$$

The corresponding BCs are

$$\begin{aligned} u_0(0) &= 0, & u_1(0) &= 0, & \frac{d^2 u_0}{dy^2}(0) &= 0, & \frac{d^2 u_1}{dy^2}(0) &= 0, \\ \theta_0(0) &= 0, & \theta_1(0) &= 0, \\ u_0(1) &= 0, & u_1(1) &= 0, & \frac{d^2 u_0}{dy^2}(1) &= 0, & \frac{d^2 u_1}{dy^2}(1) &= 0, \\ \theta_0(1) &= 1, & \theta_1(1) &= 0. \end{aligned}$$

Further, the heat transfer rate (Nusselt number) at both the walls is defined as [16]

$$Nu \mid = A_4 \left(\frac{\partial \theta}{\partial y} \right)_{y=0,1}.$$

Table 2. Comparison of present results with the results of Radhakrishna- macharya and Maiti [16] and the results obtained by NDSolve for (θ_0') $y=0$ for the Newtonian fluid case in the absence of nanoparticles, applied magnetic field, and thermal radiation.

Ec	$(\theta_0')_{y=0}$	
	RadhakrishnamacharyaPresent and Maiti [16]	NDSolve results
1	0.233	0.2315035100.231503491
2	0.308	0.3058199150.305819919
5	0.531	0.5287691340.528769167

Table 3. Comparison between the present results and NDSolve for heat transfer rate at $y = 0$ for different values of Ec , λ , and R when $R = 1$, $M = 2$, $Pr = 21$, $Ec = 0.6$, $Rd = 1$, $H = 2$, $\varepsilon = 0.001$, and $t = \pi$.

Parameter Values		$A_4(\theta')_{y=0}$	
		Present results	NDSolve
Ec	0.0	0.010559977	0.01055995
			1
	0.2	0.098651417	0.09865396
			3
	0.4	0.186748076	0.18674797
			6
λ	0.5	0.135699112	0.13569910
			3
	1	0.075075830	0.07507531
			2
	1.5	0.053645792	0.05364524
			3
R	0.5	1.311751349	1.31175715
			8
	1	0.274840147	0.27484198
			9
	1.5	0.142813289	0.14281320
			5

Now, Eqs. (10)–(13) with the appropriate BCs (14) are resolved by hiring the shooting technique with the support of the Runge–Kutta fourth-order procedure.

A comparison is made between the results obtained by present scheme with the results of Radhakrishnamacharya and Maiti [16] and with the results obtained by NDSolve for the Newtonian fluid case in the absence of nanoparticles, applied magnetic field, and thermal radiation, which are presented in Table 2. The comparison shows that there is a good agreement between the present results, the results of Radhakrishnamacharya and Maiti [16], and the results obtained by NDSolve using MATHEMATICA software. Further, to check the correctness of the present results we made a comparison between the present results and the results obtained by NDSolve using MATHEMATICA, which are given in Table 3. It is observed that there is a good agreement between the present results and the results obtained by NDSolve.

4 Result and discussion

The current segment shows the impact of the emerging parameters on the temperature heat transfer rate phase lag of temperature, and heat transfer rate of the Au + CuO-blood hybrid nanofluid with the help of pictorial presentations. For the current investigation, the considered values of various dimensionless parameters are = 0.2,

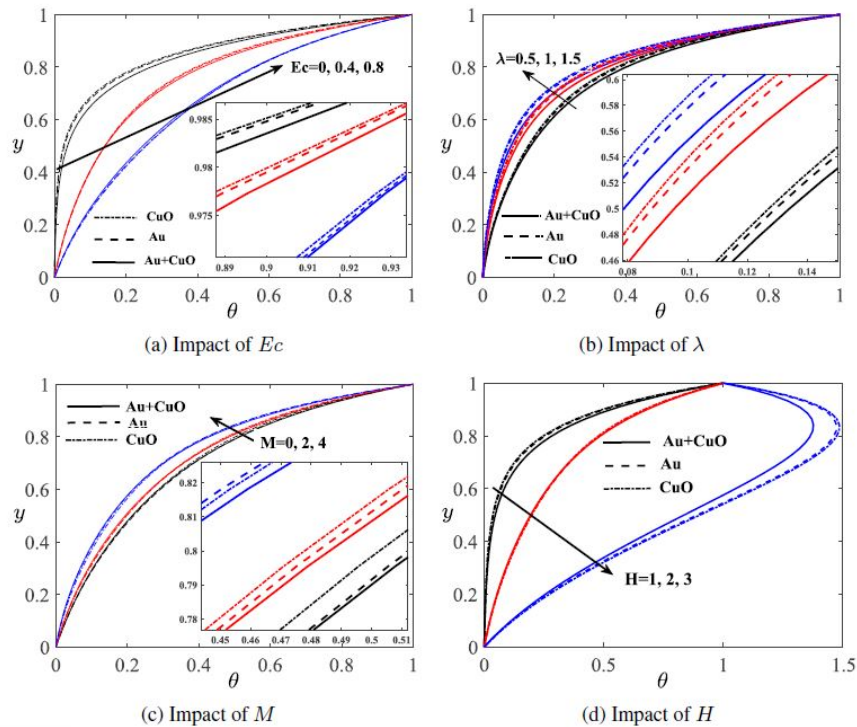


Figure 2. Temperature distribution.

$M = 2$, $H = 2$, $R = 1$, $Rd = 1$, $Pr = 21$, $Ec = 0.6$, $Q = 1$, unless otherwise stated. The graphical illustrations about the persuadence of Eckert number (Ec), Hartmann number (M), nanoparticles volume fractions, couple stress parameter, cross-flow Reynolds number (R), frequency parameter (H), radiation parameter (Rd), and the heat source/sink parameter (Q) on temperature, heat transfer rate, phase lag of temperature and heat transfer rate distributions of Au + CuO- blood hybrid nanofluid and the mono nanofluids Au-blood and CuO-blood are delineated in Figs. 2–6

The impacts of, gold nanoparticles volume fraction and copper oxide nanoparticles volume fraction, R , Rd , and Q on temperature are depicted in Figs. 2(a)–2(d) and Figs. 3(a)–3(d). Figure 2(a) illustrates the physical behavior of temperature variations of conventional nanofluids and the hybrid nanofluid for uplifting values of Ec . It is found that for all cases of Au-blood, CuO-blood nanofluids, and Au + CuO-blood hybrid nanofluid, temperature profiles are increasing with an increment in Ec . Here the characterization of Ec dissipating the energy due to the internal friction of the nanoparticles, which is suspended in the blood. The temperature distribution of hybrid nanofluid is better than conventional nanofluids. Figure 2(b) displays the influence of couple stress parameter (λ) on the variation of temperature profiles of hybrid and

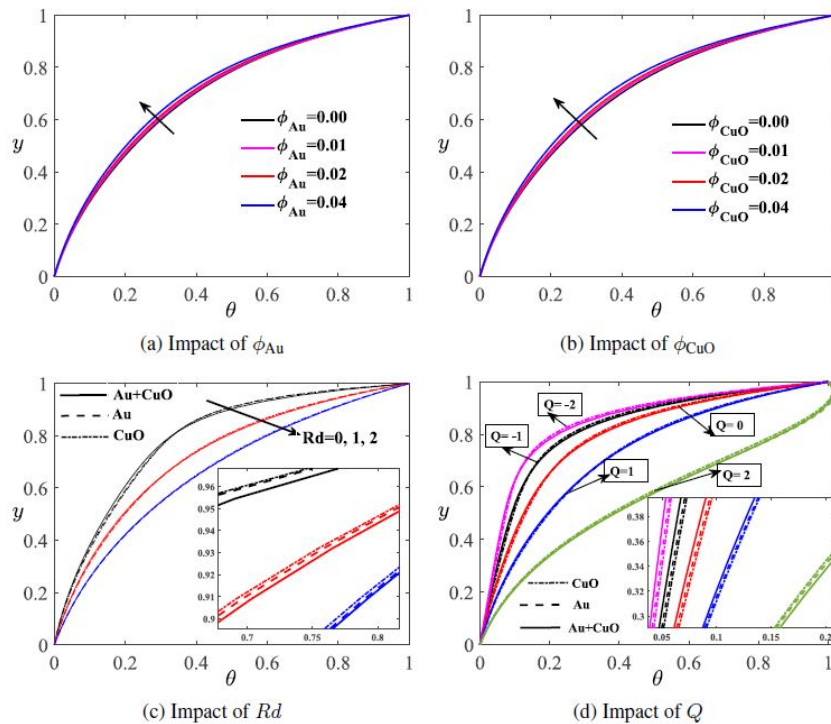


Figure 3. Temperature distribution.

conventional nanofluids. It reveals that there is a fall in the temperature with the rise of a couple stress parameter for the cases of hybrid and conventional nanofluids. From this figure one can see that Au + CuO-blood hybrid nanofluid has a significant influence on temperature variation than mono nanofluids Au-blood, CuO-blood. From Fig. 2(c) it is elucidated that the increasing Hartmann number retards the flow of electrically conducting couple stress hybrid nanofluid, which causes the decline in temperature distribution. From this one can infer that there is a fall in temperature with the high values of Hartmann number for all three cases. From the same figure it can be seen that the temperature distribution of hybrid nanofluid is greater than the conventional nanofluid near the suction wall, while it is lower near the injection wall. Figure 2(d) presents that for all three cases, there is a rise in temperature distribution with an increment in frequency parameter. The reason behind this is that increasing frequency parameter boost up the amplitude of the temperature.

From Figs. 3(a) and 3(b) one can understand that increasing volume fraction of nanoparticles Au, CuO lead to the deceleration in the temperature distribution. From Fig. 3(c) it is apparent that the raising of the radiation parameter increases the temperature of the current working fluid due to the radiation parameter has the relative commitment to the thermal transmission of conductive heat. Figure 3(d) displays the temperature distribution

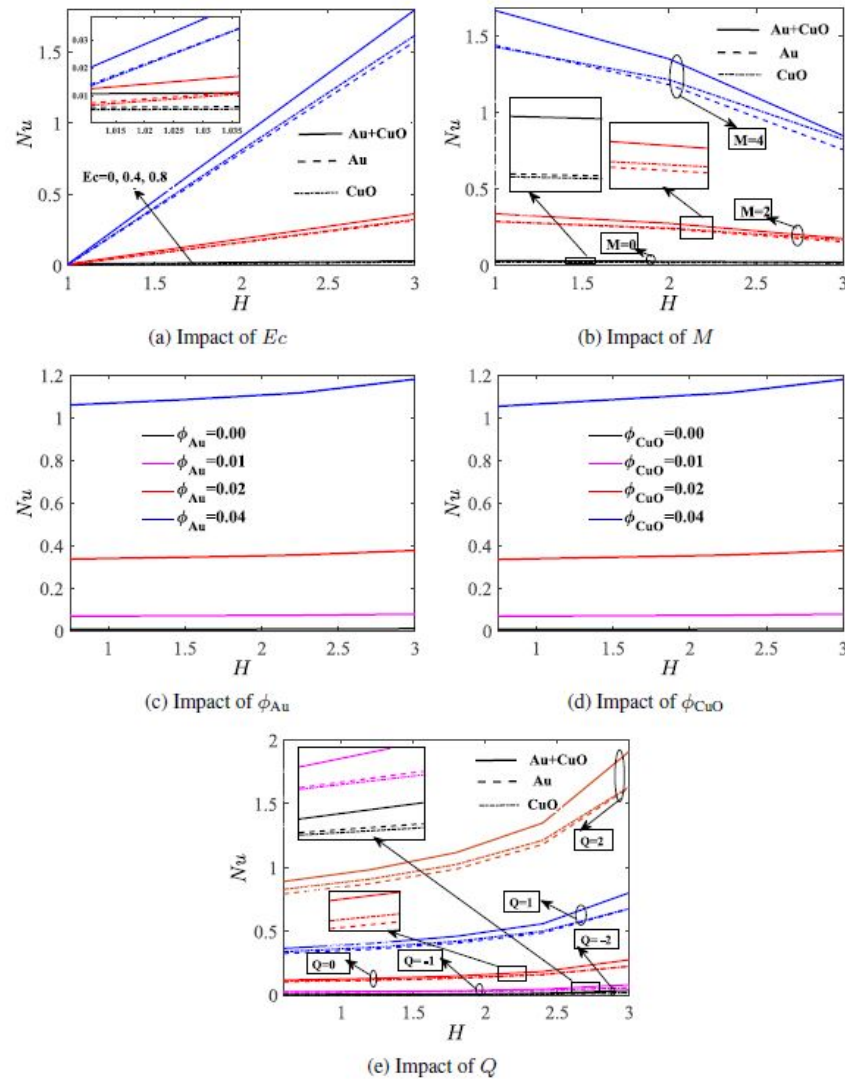


Figure 4. Heat transfer rate (Nu) against H.

for the cases of heat source and sink. Here the temperature is escalating for the uplifting values of the heat source ($Q > 0$), whereas the reverse behavior can be seen with an increasing values of the heat sink ($Q < 0$). Further, from Figs. 3(c) and 3(d) one can infer that the temperature distribution of hybrid nanofluid is better than the conventional nanofluid near the suction wall, while it is lower near the injection wall.

Figures 4(a)–4(e) are plotted to see the influence of emerging parameters Ec , M , gold nanoparticles volume fraction, copper oxide nanoparticles volume fraction,

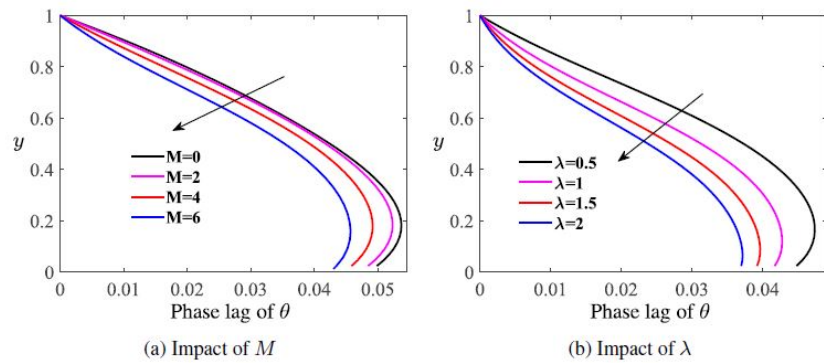
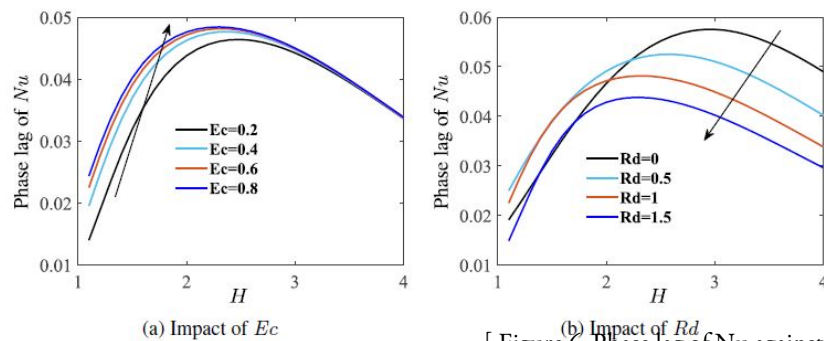


Figure 5. Phase lag of θ .



[Figure 6. Phase lag of Nu against H.]

and Q on the heat transfer rate of hybrid and mono nanofluids against the frequency parameter at the lower wall $y = 0$. From these figures it is observed that the rate of heat transfer of hybrid nanofluid is higher than the heat transfer rate of conventional nanofluid. Figure 4(a) displays that the heat transfer rate is enhancing for various values of Eckert number, which is due to the increasing viscous dissipation escalating the rate of heat transfer. Figure 4(b) demonstrates that a rise in magnetic parameter increases the rate of heat transfer because of the retarding forces making the flow slowdown, which is created by the magnetic field. From Figures 4(c) and 4(d) it is portrayed that Nu is getting a boost up with the rising volume fractions of gold and copper oxide nanoparticles, thanks to the high thermal conductivity of the nanoparticles. Figure 4(e) illustrates that the heat transfer rate is increasing with an increment in the heat source, whereas the opposite behavior can be found for the higher values of the heat sink.

Figures 5(a)–5(b) display the variation of phase lag of the temperature of couple stress hybrid nanofluid for different values of Hartmann number and the couple stress parameter. From the same figures one can infer that phase lag decreases with increasing values of Hartmann number and couple stress parameter and the phase lag is maximum near to the injection wall of the channel. The phase lag variation of heat transfer rate of couple stress hybrid nanofluid against the frequency parameter for the influences of Eckert number and the radiation parameter are displayed in Figs. 6(a)–6(b). Figure 6(a) shows that increasing viscous dissipation encouraging the phase lag of heat transfer rate and the maximum of

the phase lag is near to the suction wall. Figure 6(b) elucidates that the maximum of phase lag of heat transfer rate is near to the suction wall of the channel, which is observed by increasing the thermal radiation.

5 Conclusion

In the current work, the hydromagnetic pulsatile flow of blood-based conducting couple stress hybrid nanofluid with the influences of Ohmic heating, heat source/sink, and thermal radiation has been discussed. The considered model is important in the study of biomedical engineering and nano-drug delivery. The numerical outcomes for dimensionless flow parameters are achieved by adopting the shooting method with the aid of the Runge–Kutta fourth-order scheme. The dynamics of blood flow is analyzed for hybrid nanofluid and conventional mono nanofluids. The main outcomes of the current analysis are summarized as follows:

- Temperature is raising for the magnifying Eckert number, whereas the reverse behavior can be found with a rise in couple stress parameter.
- An increment in volume fractions of gold and copper oxide nanoparticles decelerates the profiles of temperature distribution. The reverse trend can be seen with an escalation of radiation parameter.
- Temperature is increasing with the rising values of heat source and the increasing heat sink decreasing the temperature.
- The heat transfer rate is getting high with the high values of the Ec , and the same behavior is noticed with the uplifting magnetic field.
- The profiles of heat transfer rate distribution are increasing with a rise in volume fractions of gold and copper oxide nanoparticles.
- Phase lag of temperature is decreasing for the high values of M and λ . Phase lag of Nu is increasing with increasing values of Ec .

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