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Hybrid Nanofluid Flow with Multiple Slips Over a Permeable Stretching/Shrinking Sheet Embedded in a Porous Medium

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ABSTRACT

Including slip boundary conditions in the study involving the flow of foams, emulsions, polymer solutions, and suspensions over moving surfaces are crucial for real-life applications. The current study analysed the multiple slips effects on the magnetohydrodynamics (MHD) flow of Ag-CuO/water hybrid nanofluid past a permeable stretching/shrinking sheet embedded in a porous medium. Appropriate similarity variables are introduced for transforming the governing equations and boundary conditions into ordinary differential equations before being solved using the bvp4c solver. Dual solutions are yielded from the numerical computation of flow over a shrinking sheet, and the first solution is identified as stable through a stability analysis. It is found that the imposition of velocity, thermal, and mass slips promotes the reduction of momentum, thermal, and concentration boundary layer thickness, respectively. The hybrid nanofluid around the sheet is observed to flow at a different velocity from the sheet due to the imposition of velocity slip. Thermal and mass slips, meanwhile, obstruct the flow's ability to transport heat and mass. An increased suction parameter, however, can aid in enhancing the rates of heat and mass transfers.

1. Introduction

A hybrid nanofluid consists of two or more different nanoparticles dispersed in a base fluid. The fluid is usually utilised as a coolant in radiators, heat exchangers, chemical engineering processes, refrigerators, nuclear systems, and solar collectors [1-3]. Sidik *et al.,* [4] presented a comprehensive description of hybrid nanofluids' preparation and thermal performance. Other studies on hybrid nanofluids were also conducted by Dinarvand *et al.,* [5], Berrehal *et al.,* [6], and Yahaya *et al.,* [7]. Two models are commonly employed in studying hybrid nanofluids' rheological and thermal behaviours: the Tiwari and Das model [8] and the Buongiorno model [9]. The single-phase Tiwari and Das model incorporate the effects of nanoparticle volume fraction in heat transfer enhancement with the thermophysical properties expressed as functions of the nanoparticles and the base fluid [10]. In

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contrast, the two-phase Buongiorno model considers the movement of nanoparticles (i.e., through Brownian diffusion and thermophoresis) in improving the heat transfer performance of nanofluids and hybrid nanofluids. Waini *et al.,* [11] employed a combination of these models to discuss a hybrid nanofluid's heat transfer and flow. It was found that the nanoparticle concentration rises with the Brownian motion parameter, and the thermophoresis parameter reduces the temperature and nanoparticle concentration of the hybrid nanofluid. Sulochana and Aparna [2] then observed that the heat transfer rate depreciates with the increase in Brownian motion, nanoparticle volume fraction, radiation, and thermophoresis parameters, and the magnetic field helps in regulating the flow and heat transfer rate of the Al-Cu/water hybrid nanofluid. In real-life applications, the slip boundary condition may exist during the polishing of artificial heart valves, melting of polymers, drug delivery systems, microelectronic cooling systems, and micro heat exchangers [12,13]. Usman *et al.,* [14] discussed the velocity slip effects on hybrid nanofluid flow over a permeable surface. The slip parameter was noted to inhibit the fluid velocity and reduces the skin friction coefficient. However, Nadeem and Abbas [15] observed that this parameter enhanced the velocity profile of micropolar hybrid nanofluid in stagnation point flow. Meanwhile, thermal slip in the flow boosts skin friction but reduces the heat transfer rate. Ullah *et al.,* [16] obtained the opposite result for flow over an infinite disk with thermal radiation. Eid and Nafe [17] noted that the thermal slip parameter affects the flow over the stretching sheet differently from the shrinking sheet. Besides that, many researchers have studied hybrid nanofluid flow with slip boundary conditions [18-22]. However, most of these studies did not consider the effects of mass slip on the hybrid nanofluid flow.

Therefore, we will investigate the effects of multiple slips (i.e., velocity, thermal, and mass slips) on hybrid nanofluid flow. The present study will consider the magnetohydrodynamics flow of a hybrid Ag-CuO/water nanofluid over a sheet embedded in a porous medium. A combination of the Buongiorno model and the Tiwari and Das model will be employed in the mathematical formulation of the flow problem. Then, similarity transformations will reduce and prepare the governing equations and boundary conditions for a numerical computation utilising a built-in MATLAB bvp4c solver. All results will be tabulated and displayed graphically as concentration, velocity, and temperature profiles. The numerical results generated in this study will provide a significant analysis of hybrid nanofluid flow having multiple slips and the above-stated conditions.

2. Problem Geometry and Mathematical Formulation

A steady, two-dimensional MHD flow of an aqueous Ag-CuO hybrid nanofluid past a vertical stretching/shrinking sheet embedded in a porous medium is considered in this study. The assumption of an adequately small magnetic Reynolds number allows the neglection of the induced magnetic field. Cartesian coordinates are implemented to represent the geometry of the flow problem with u and v as the velocities in the x- and y-directions, respectively. Along the x-axis, a permeable sheet is assumed to move with a stretching/shrinking velocity of u_w. It has a constant wall temperature and nanoparticle concentration of $T_w > T_\infty$ and $C_w > C_\infty$, respectively. Meanwhile, the mass transfer velocity, v_w and magnetic field, B_0, are imposed in the y-direction. The thermophysical properties of the nanoparticles are given by Hayat *et al.,* [23].

The governing equations are expressed as [24]

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{hnf}}\left[\mu_{hnf}\frac{\partial^2 u}{\partial y^2} - \frac{\mu_{hnf}}{K_p}u - \sigma_{hnf}B_0^2 u\right], \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{(\rho C_p)_{hnf}}\left[k_{hnf}\frac{\partial^2 T}{\partial y^2}+\frac{\left[(\rho C_p)_{hnf}\right]^2}{(\rho C_p)_f}\left[\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2+D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right]\right], \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}+D_B\frac{\partial^2 C}{\partial y^2}. \tag{4}$$

In the equations, ρ, ρC_p k, σ, and μ represent the density, heat capacity, thermal conductivity, electrical conductivity, and viscosity with the suffixes of hnf and f for hybrid nanofluid and base fluid, respectively. The correlations of these physical properties can be obtained from Devi and Devi [25]. Meanwhile, K_p is the permeability of the porous medium, D_B is the Brownian diffusion coefficient, and D_T is the thermophoretic diffusion coefficient. The appropriate boundary conditions are given by

$$\text{At } y=0: \quad u=\lambda u_w+A_1\nu_{hnf}\frac{\partial u}{\partial y}, \qquad v=v_w, \qquad T=T_w+B_1\frac{\partial T}{\partial y}, \qquad C=C_w+C_1\frac{\partial C}{\partial y}, \tag{5}$$

$$\text{as } y\to\infty: \quad u\to 0, \qquad T\to T_\infty, \qquad C\to C_\infty, \tag{6}$$

where $u_w=mx/L$ with m as a constant and L as the characteristic length. A_1, B_1, and C_1 are the velocity, thermal, and mass slips factors, respectively. Whereas $\nu_{hnf}=\mu_{hnf}/\rho_{hnf}$ is the kinematic viscosity.

The following similarity transformations, with ψ as the stream function and η as the similarity variable, are introduced

$$\psi=\frac{mx}{L}\sqrt{K_p}f(\eta), \ \ \eta=\frac{y}{\sqrt{K_p}}, \ \ u=\frac{\partial\psi}{\partial y}, \ \ v=-\frac{\partial\psi}{\partial x}, \ \ \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, \ \ \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}, \tag{7}$$

and substituted into Eq. (1) to Eq. (6) to produce the following nonlinear ordinary differential equations

$$f'''=f'-(1-\varphi_1)^{2.5}(1-\varphi_2)^{2.5}ReDa\left[\left(\varphi_2\frac{\rho_2}{\rho_f}+(1-\varphi_2)\left((1-\varphi_1)+\varphi_1\frac{\rho_1}{\rho_f}\right)\right)\left(ff''-f'^2\right)-\frac{\sigma_{hnf}}{\sigma_f}Mf'\right], \tag{8}$$

$$\theta''=-\frac{k_f}{k_{hnf}}\left(\varphi_2\frac{(\rho C_p)_2}{(\rho C_p)_f}+(1-\varphi_2)\left((1-\varphi_1)+\varphi_1\frac{(\rho C_p)_1}{(\rho C_p)_f}\right)\right)Pr\left(Nb\phi'\theta'+Nt\theta'^2+ReDaf\theta'\right), \tag{9}$$

$$\phi''=-ReDaLef\phi'-\frac{Nt}{Nb}\theta'', \tag{10}$$

$$\left.\begin{array}{c} f'(0)=\lambda+af''(0), \quad f(0)=S, \quad \phi(0)=1+c\phi'(0), \quad \theta(0)=1+b\theta'(0) \\ f'(\eta)\to 0, \quad \phi(\eta)\to 0, \quad \theta(\eta)\to 0 \quad \text{as } \eta\to\infty \end{array}\right\}. \tag{11}$$

In the equations, f, θ, and ϕ are functions related to velocity, temperature, and nanoparticle concentration, respectively, and the prime notation indicates differentiation with respect to η.

Meanwhile, φ is the volume fractions of individual nanoparticles, and λ is the stretching/shrinking parameter. In addition,

$$Re=\frac{mL}{\nu_f},\quad Da=\frac{K_p}{L^2},\quad M=\frac{\sigma_f B_0^2 L}{m\rho_f},\quad Pr=\frac{\mu_f(\rho C_p)_f}{\rho_f k_f},\quad Nb=\frac{\left(\frac{(\rho C_p)_{hnf}}{(\rho C_p)_f}\right)D_B(C_w-C_\infty)}{\nu_f},$$

$$Nt=\frac{\left(\frac{(\rho C_p)_{hnf}}{(\rho C_p)_f}\right)D_T(T_w-T_\infty)}{\nu_f T_\infty},\quad Le=\frac{\nu_f}{D_B},\quad S=-\frac{v_w L}{m\sqrt{K_p}},\quad a=\frac{A_1\nu_f}{\sqrt{K_p}},\quad b=\frac{B_1}{\sqrt{K_p}},\quad c=\frac{C_1}{\sqrt{K_p}},$$

with Re as the Reynolds number, Da as the Darcy number, M as the magnetic field parameter, Pr as the Prandtl number, Nb as the Brownian motion parameter, Le as the Lewis number, S as the suction parameter, a as the velocity slip parameter, b as the thermal slip parameter, c as the mass slip parameter, and Nt as the thermophoresis parameter.

Lastly,

$$C_{fx}Re_x Da_x^{0.5}=2\frac{\mu_{hnf}}{\mu_f}f''(0),\quad Nu_x Da_x^{0.5}=-\frac{k_{hnf}}{k_f}\theta'(0),\quad \text{and}\quad Sh_x Da_x^{0.5}=-\phi'(0), \tag{12}$$

are the dimensionless skin friction coefficient ($C_{fx}Re_x Da_x^{0.5}$), Nusselt number ($Nu_x Da_x^{0.5}$), and Sherwood number ($Sh_x Da_x^{0.5}$) with the local Darcy number of $Da_x=K_p/x^2$ and local Reynolds number of $Re_x=xu_w/\nu_f$.

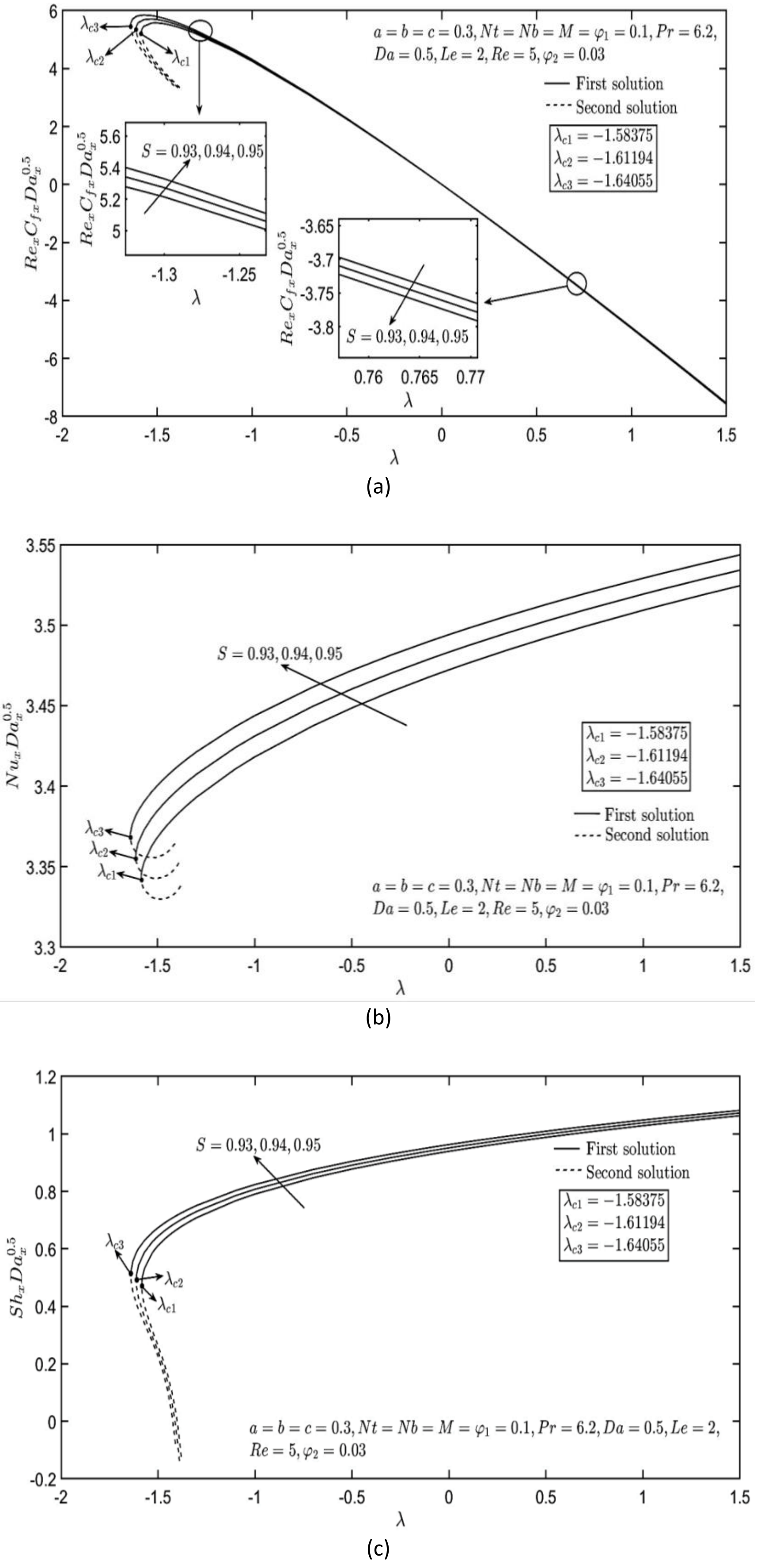
3. Results and Discussion

The influence of various dimensionless controlling parameters on the flow of Ag-CuO/water hybrid nanofluid is analysed. All numerical computations are executed in MATLAB (bvp4c solver), and the results are recorded in graphs and tables. To ascertain whether the numerical procedure used in this study is correct, the present and previous results are compared in Table 1. Since the earlier results obtained through the homotopy analysis method (HAM) agree with the present results computed using the bvp4c solver, it verifies that the numerical procedure used in this study is correct.

Table 1
Comparison of $-\theta'(0)$ and $-f''(0)$ for various values of $a, b, c,$ and Da at $Pr=6.8, Re=5.0, \lambda=1.0, Le=5.0, M=S=\varphi_1=\varphi_2=0,$ and $Nb=Nt=0.1$

a	b	c	Da	$-f''(0)$		$-\theta'(0)$	
				Present results	Previous results [24]	Present results	Previous results [24]
0.5	0	0	0	0.66667	0.66666	0.04696	0.04696
	0.5			0.66667	0.66667	0.04631	0.04631
0.2	0.2	0.2	0.7	1.36746	1.36746	1.41331	1.41331

Figure 1 shows dual solutions with various values of suction and stretching/shrinking parameters. At particular values of the controlling parameters, two solutions are obtained for the shrinking sheet case. Based on the stability analysis of multiple solutions performed in the previous studies, only the first solution is identified as stable and physically meaningful [26-29]. Therefore, the subsequent discussion will focus on the first solution.



(a)

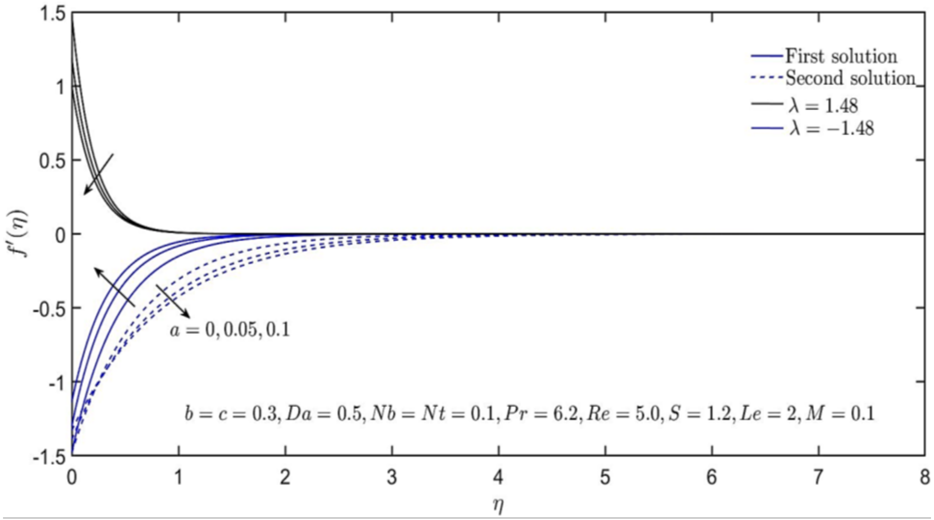
(b)

(c)

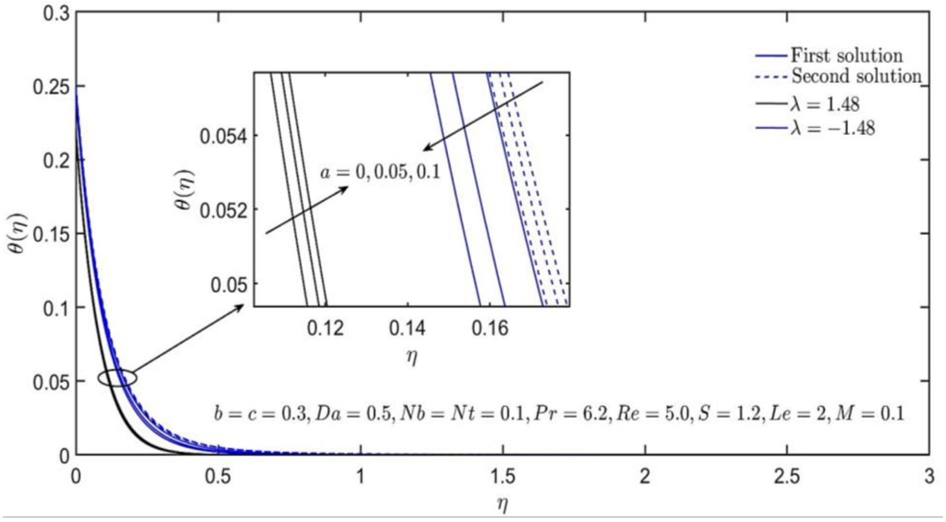
Fig. 1. (a) Local skin friction coefficient, (b) local Nusselt number, and (c) local Sherwood number with various values of S and λ

For shrinking and stretching cases, an increase in the suction parameter has differing effects on the skin friction coefficient (see Figure 1(a)). Meanwhile, Figure 1(b) and (c) show that the local Nusselt number and Sherwood number for the shrinking and stretching cases increase. The application of suction pulls the fluid closer to the sheet. Consequently, it enhances the rate of heat and mass transfers at the sheet's surface. These behaviours are represented by the augmentation of the local Nusselt and Sherwood numbers, as in Figure 1(b) and (c).

The velocity profile for stretching and shrinking sheets cases with various values of a are presented in Figure 2(a). As slip is imposed at the sheet surface, the velocity of the hybrid nanofluid near the surface becomes unequal to the ones of the stretching and shrinking sheets. Later, causing the decrease and increase of the velocity profile for flow over the stretching and shrinking sheets, respectively. As observed in Figure 2(b) and (c), the temperature and concentration profiles for $\lambda > 0$ increase as the value of a rises. Consequently, the boundary layers thicken and reduce the temperature and concentration gradients.



(a)



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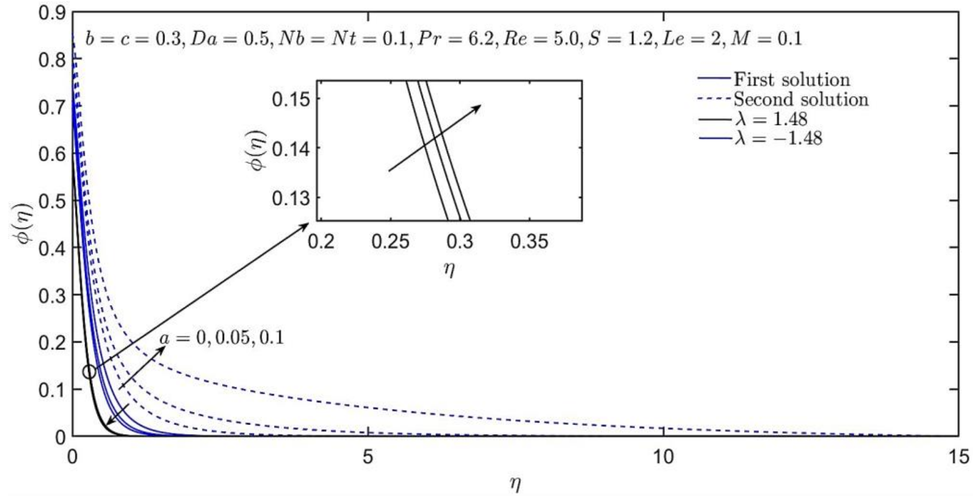
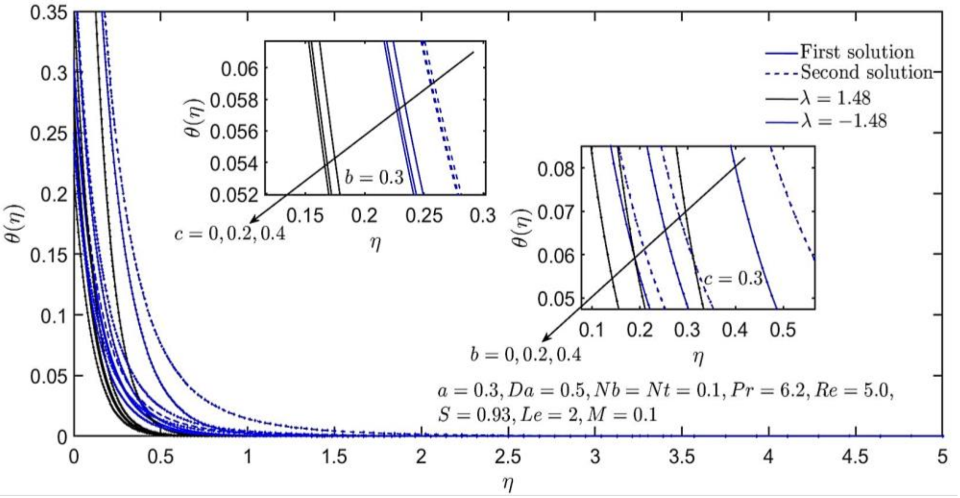


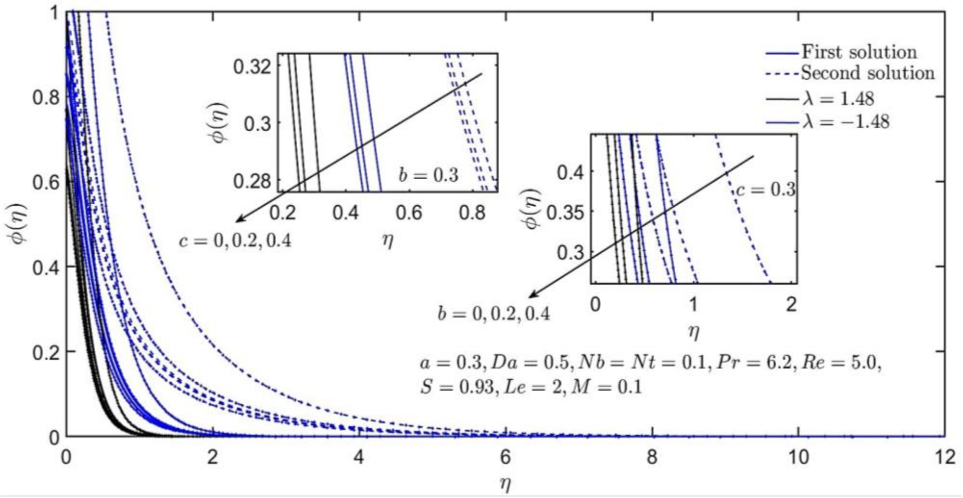
(c)

Fig. 2. Effects of a on (a) velocity, (b) temperature, and (c) concentration profiles

The thermal slip parameter b and mass slip parameter c do not significantly impact the velocity profile. However, the increasing values of b and c reduce the temperature profile and constrict the thermal boundary layer in Figure 3(a). The imposition of thermal and mass slips impedes the heat transfer within the flow, which reduces the heat transfer rate and temperature profile of the hybrid nanofluid. Similarly, the increment of b and c also causes the reduction of the concentration profile, as shown in Figure 3(b). Mahabaleshwar *et al.,* [30] noted the same behaviour in hybrid nanofluid flow with mass slip over a porous stretching sheet. The mass slip inhibits the mass transfer performance in the flow and reduces the mass transfer rate. Hence, reducing the concentration profile for flow over the stretching and shrinking sheets.



(a)



(b)

Fig. 3. Effects of b and c on (a) temperature and (b) concentration profiles

4. Conclusion

The magnetohydrodynamics flow of Ag-CuO/water hybrid nanofluid, induced by a permeable stretching/shrinking sheet embedded in a porous medium, is analyzed. The governing equations and boundary conditions are reduced to ordinary differential equations using similarity transformations. Then, the bvp4c solver is utilized for numerical computations. Multiple solutions for the shrinking sheet case are obtained, and the first solution is deemed stable and physically meaningful. The imposition of velocity, thermal, and mass slips reduces the thickness of the momentum, thermal, and concentration boundary layers. The heat and mass transfers within the flow are impeded by the imposition of thermal and mass slips. However, the augmentation of suction helps improve the rates of heat and mass transfers in the flow.

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