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MHD Hybrid Nanofluid Flow over a Stretching/Shrinking Sheet with Skin Friction: Effects of Radiation and Mass Transpiration

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Abstract: The study of inclined magnetohydrodynamics (MHD) mixed convective incompressible flow of a fluid with hybrid nanoparticles containing a colloidal combination of nanofluids and base fluid is presented in the current research. Al_2O_3-Cu/H_2O hybrid nanofluid is utilized in the current analysis to enhance the heat transfer analysis. The impact of radiation is also placed at energy equation. The main research methodology includes that the problem provided equations are first transformed into non-dimensional form, and then they are obtained in ordinary differential equations (ODEs) form. Then using the solutions of momentum and transfers equations to solve the given ODEs to get the root of the equation. The main purpose includes the resulting equations are then analytically resolved with the aid of suitable boundary conditions. The results can be discussed with various physical parameters viz., stretched/shrinked-Rayleigh number, stretching/shrinking parameter, Prandtl number, etc. Besides, skin friction and heat transfer coefficient can be examined with suitable similarity transformations. The main significance of the present work is to explain the mixed convective fluid flow on the basis of analytical method. Main findings at the end we found that the transverse and tangential velocities are more for more values of stretched/shrinked-Rayleigh number and mass transpiration for both suction and injection cases. This is the special method it includes stretched/shrinked-Rayleigh number, it contributes major role in this analysis. The purpose of finding the present work is to understand the analytical solution on the basis of mixed convective method.

Keywords: nanofluid; porous medium; skin friction; heat transfer; radiation; inclined MHD

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1. Introduction

Researchers show interest in stretching sheet problems with hybrid nanofluid due to its numerous significances in many fields, viz., production of paper, the creation of rubber sheets, numerous technological uses, etc. The model for a nanofluid motion induced by a stretching (shrinking) sheet was considered in [1]. The hybrid nanofluid, which is made up of various nanoparticles dispersed in the base fluid, has recently been introduced as an idea for enhancing nanofluids. It is anticipated that it will provide more substantial thermophysical and rheological characteristics, as well as improving heat transfer properties. Further, the magnetohydrodynamics (MHD) focuses on how an electrically conducting fluid moves in a magnetic field, which may be used to control how the system transfers heat. Theoretically, magnetic fields might cause the Lorentz force, a drag force that slows the flow of a fluid and raises its temperature and concentration in a flowing medium. The rate of thermal efficiency will be increased by hybrid nanofluid. When there is a problem with the sheet stretching, heat transfer can be used to determine a product's quality. The problem of stretching sheet was initiated by Sakiadis 1961 (a,b) [2,3] and obtained the solution of flow problems involving continuously moving surfaces. Crane [4] expanded this for the stretching surfaces for the viscous flow with the distance linearly varying from the slit. MHD Casson flow past a stretching sheet is investigated computationally by Kumar et al. [5]. In the presence of a stretching sheet, Anderson et al. [6,7] examined the MHD power law fluid and viscoelastic fluid. Later, a great deal of study was done on fluid flow in the presence of nanofluid and hybrid nanofluid with different features such as radiation and mass transpiration. Aly [8] and Hassan [9] investigated the nanofluid flow over a porous stretching/shrinking sheet with the effect of MHD, radiation, partial slip and also suction/injection effects. Anusha et al. [10,11] explains the flow velocity due to the presences of nanoparticles in the base fluid by considering MHD effect, mass transpiration, Brinkman effect over a porous stretching/shrinking surface. The research on the most current development of hybrid nanofluid carried out by Sarkar et al. [12] used three different types of base fluid; he draws the conclusion that the right hybridization process is most beneficial for the hybrid nanofluids thermal efficiency. Devi and Devi [13] carried out an investigation with Cu-Al_2O_3/H_2O hybrid nanofluid in the presence of stretching sheet. Mishra et al. [14] worked on MHD nanofluid flow along with Soret and Dufour effects in the presence of stenosed artery with variable viscosity. Sharma et al. [15] studied the EMHD Jeffrey nanofluid flow with entropy generation and thermal radiation. Then, Gandhi et al. [16] discussed the applications of Koo–Kleinstreuer–Li Correlations by using computer simulations of EMHD Casson nanofluid. In this work, the authors deal with a non-Newtonian nanofluid blood flow incorporating CuO and Al_2O_3 nanoparticles and perform an electromagnetohydrodynamic analysis under external fields, finding that it can be helpful in the diagnosis of hemodynamic irregularities.

In the recent developments, as a development of nanofluid, hybrid nanofluid is introduced; it is made by mixing two different types of nanoparticles with the base fluids, and this is expected to provide an extra characteristic namely thermophysical and rheological characteristics. Hybrid nanofluid is widely used in many heat transfer fields, as it is shown in Ref. [17].

With careful observations of above articles, the present work examines the dual nature of a MHD heat transfer of a fluid with radiation and inclined angle. The main objective includes that the given partial differential equations (PDEs) are first converted into non-dimensional form and then transformed into ordinary differential equations (ODEs). Exact analytical solutions are then obtained using suitable manipulation and this study has been achieved with the help of various physical parameters. In addition, skin friction and Nusselt number can be verified analytically with suitable parameters. The present work contains numerous industrial applications, such as blowing of glass and extrusion of growing crystal, in the field of polymer sheets as well as cooling of metallic plates. The manuscript is organized as follows: in Section 2, the problem is presented and the analytical solution is given. In Section 3, the results are commented on and discussed. In particular, we show how dimensionless transverse and tangential velocity spatially behave, as well as the effect of the Prandtl number on Skin friction and the impact of the Rayleigh number on the Nusselt number for several values of the parameters. Finally, the conclusions are exposed in Section 4.

2. Mathematical Analysis

The current study takes into account a Newtonian fluid flow with inclined angled MHD on the surface of Al_2O_3-Cu-H_2O hybrid nanofluid particles. The flow is mixed convective and the radiation is also present in the heat transfer equation. Here, the initial equations are in the form of mixed convection, and these equations are solved analytically. The Cartesian coordinate systems (x,y) are introduced with its origin schematically indicated in Figure 1. The hybrid nanofluid physical properties are explained in Table 1. These suppositions allow for the following modifications to be made to N-S equations: [18–20]:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu_{hnf}\frac{\partial^2 u}{\partial y^2}+\vec{g}\beta(T-T_\infty)-\frac{\sigma_{hnf}{B_0}^2}{\rho_{hnf}}Sin^2(\tau)u \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\chi_{hnf}\frac{\partial^2 T}{\partial y^2}-\frac{1}{(\rho C_p)_{hnf}}\frac{\partial q_r}{\partial y} \tag{3}$$

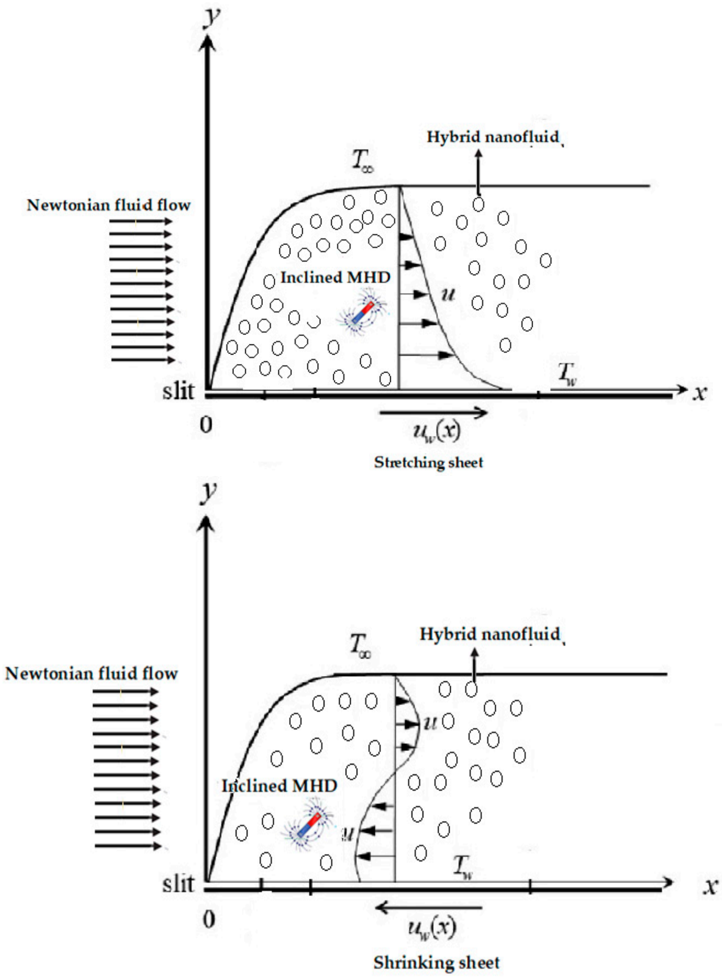


Figure 1. Schematic diagram of problem setup.

The B. Cs supported to motion equations are [21,22]

$$\left.\begin{array}{c} u=d\alpha x, \\ v=V_w, \\ T=T_\infty+\gamma(T_w-T_\infty)x \end{array}\right\} \text{ at } y=0 \tag{4a,b,c}$$

$$u=0\,,\;T\to T_\infty \qquad \text{as} \quad y\to\infty \tag{4d,e}$$

here, Equation (4a,b,c) indicate the linear stretching in x direction, compatible condition, stretching of the sheet and it excludes dynamics at the distance away from the field, respectively. It also (4d,e) indicates temperature along the plate along with x axis, and distance for away from the plate, respectively.

According to Rosseland, the approximation thermal radiation can be simplified as (See Refs. [23–27])

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{5}$$

here, expand T^4 on the basis of Taylor's series and ignored some terms to get the equation as

$$T^4 = 4{T_\infty}^3 T - 3{T_\infty}^4 \tag{6}$$

Upon inserting Equation (6) into Equation (5), the following outcome is obtained.

$$\frac{\partial q_r}{\partial y} = -\frac{16{T_\infty}^3\sigma^*}{3k^*}\frac{\partial T^2}{\partial y^2} \tag{7}$$

Next, we use the following dimensionless variables for further calculation [28,29]

$$\left.(X,Y) = \sqrt{\frac{\alpha}{\nu}}(x,y),\ \ (U,V) = \frac{(u,v)}{\sqrt{\alpha\nu}} \quad \theta = \frac{T - T_\infty}{T_w - T_\infty},\right\} \tag{8}$$

With the help of the above Equation (8) to change Equation (1) to (3) as given below [30]

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{9}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = \frac{\varepsilon_1}{\varepsilon_2}\frac{\partial^2 U}{\partial Y^2} + \frac{Ra_s}{\mathrm{Pr}}\theta - \frac{\varepsilon_3}{\varepsilon_2}M\,Sin^2(\tau)U = 0 \tag{10}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{\mathrm{Pr}}\left(\frac{\varepsilon_1}{\varepsilon_2} + \frac{R}{\varepsilon_4}\right)\frac{\partial^2\theta}{\partial Y^2} \tag{11}$$

The parameters used in Equation (6)–(8) can be defined as
$\lambda = \frac{\gamma}{\sqrt{\frac{\alpha}{\nu}}}$, stretching/shrinking boundary,
$Ra_s = \frac{\beta g(T_w - T_\infty)}{\nu\chi}\left(\frac{\nu}{\alpha}\right)^{3/2}$, stretched/shrinked-Rayleigh number
$\mathrm{Pr} = \frac{\nu}{\chi}$, Prandtl number.
$M = \frac{\sigma_f {B_0}^2}{\rho_f \alpha}$ indicates magnetic parameter.
$R = \frac{16\sigma^* {T_\infty}^3}{3k^*\kappa_f}$ indicates radiation parameter.
The constant parameters of Equations (9)–(11) can be defined as follows

$$\varepsilon_1 = \frac{\mu_{hnf}}{\mu_f} = \frac{1}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}},$$

$$\varepsilon_2 = (1-\phi_2)\left(1 - \phi_1 + \phi_1\frac{\rho_{S_1}}{\rho_f}\right) + \phi_2\frac{\rho_{S_2}}{\rho_f},$$

$$\varepsilon_3 = \frac{\sigma_{hnf}}{\sigma_f} = \sigma_{bf}\left(\frac{\sigma_{s_2}(1+2\phi_2) + 2\sigma_{bf}(1-\phi_2)}{\sigma_{s_2}(1-\phi_2) + \sigma_{bf}(2+\phi_2)}\right)$$

where,

$$\sigma_{bf} = \sigma_f\left(\frac{\sigma_{s_1}(1+2\phi_1) + 2\sigma_f(1-\phi_1)}{\sigma_{s_1}(1-\phi_1) + \sigma_f(2+\phi_1)}\right)$$

$$\varepsilon_4 = \frac{(\rho C_p)_{hnf}}{(\rho C_p)_f} = (1-\phi_2)\left(1 - \phi_1 + \phi_1\frac{(\rho C_p)_{S_1}}{(\rho C_p)_f}\right) + \phi_2\frac{(\rho C_p)_{S_2}}{(\rho C_p)_f}$$

Table 1. Heat-transfer characteristics of hybrid nanofluids (see Refs. [30–35]).

SR. No.	Thermophysical Properties	Liquid Phase (Water)	Copper	Alumina
1	C_P (J/kgK)	4179	385	765
2	ρ (kg/m^3)	997.1	8933	3970
3	κ (W/mK)	0.613	400	40
4	σ (Sm^{-1})	0.05	5.97×10^7	35×10^6

Introduce a stream function $\psi(x, y)$, and the velocities u & v in terms of $\psi(x, y)$, as follows

$$\psi(X, Y),\ U = \frac{\partial \psi}{\partial Y},\ V = -\frac{\partial \psi}{\partial X} \tag{12}$$

Inserting Equation (12) in Equations (10) and (1), to yield the following equations [36]

$$\frac{\varepsilon_1}{\varepsilon_2}\frac{\partial^3 \psi}{\partial Y^3} + \frac{\partial\left(\psi, \frac{\partial \psi}{\partial Y}\right)}{\partial(X, Y)} + \frac{Ra_s}{\mathrm{Pr}}\theta - \frac{\varepsilon_3}{\varepsilon_2}M\,Sin^2(\tau)\frac{\partial \psi}{\partial Y} = 0 \tag{13}$$

$$\left(\frac{\varepsilon_1}{\varepsilon_2} + \frac{R}{\varepsilon_4}\right)\frac{\partial^2 \theta}{\partial Y^2} + \mathrm{Pr}\frac{\partial(\psi, \theta)}{\partial(X, Y)} = 0 \tag{14}$$

Reduces B. Cs are as follows [37]

$$\left.\begin{array}{l} \frac{\partial \psi}{\partial Y} = dX,\ -\frac{\partial \psi}{\partial X} = V_C,\ \theta = \lambda X \ \text{ at } \ Y = 0 \\ \frac{\partial \psi}{\partial Y} = 0,\quad \theta \to 0 \quad \text{as} \quad Y \to \infty \end{array}\right\} \tag{15a,b}$$

The solution of Equations (13) and (14) can be assumed as

$$\psi = Xf(Y), \quad \theta = \lambda X f_1(Y) \tag{16}$$

On substituting Equation (16) into Equations (13) and (14) to obtain the following results

$$\frac{\varepsilon_1}{\varepsilon_2}\frac{d^3 f_1}{dY^3} + f\frac{d^2 f_1}{dY^2} - \left(\frac{df}{dY}\right)^2 + \frac{Ra_s}{\mathrm{Pr}}\lambda f_1 - \frac{\varepsilon_3}{\varepsilon_2}M\,Sin^2(\tau)\frac{df}{dY} = 0 \tag{17}$$

$$\left(\frac{\varepsilon_1}{\varepsilon_2} + \frac{R}{\varepsilon_4}\right)\frac{d^2 f_1}{dY^2} + \mathrm{Pr}\left(f\frac{df_1}{dY} - \frac{df}{dY}f_1\right) = 0 \tag{18}$$

B.Cs related to f and f_1 can be yielded by substituting Equation (16) in Equation (15a,b)

$$\begin{array}{c} f(0) = V_C,\ \left(\frac{df}{dY}\right)_{\eta=0} = d,\ \left(\frac{df}{dY}\right)_{\eta\to\infty} \to 0 \\ f_1(0) = 1, \quad f_1(\infty) \to 0 \end{array} \tag{19}$$

Assume Equation (17) has a solution that takes the form

$$f(Y) = V_C + d\left(\frac{1 - e^{-\delta Y}}{\gamma}\right),\ f_1(Y) = e^{-\delta Y} \tag{20}$$

Using the above assumed solution into Equation (17) to yield the result given below.

$$\delta = \frac{V_C \pm \sqrt{V_C{}^2 + 4\varepsilon_1 d(\varepsilon_2 d^2 - \frac{Ra_s}{\mathrm{Pr}}\lambda\varepsilon_2 + \varepsilon_3 M\,Sin^2(\tau)d)}}{2\varepsilon_1 d} \tag{21}$$

To increase the results of this paper, we introduce the global quantities Skin friction (C_f) and Nusselt number (Nu) as follows

$$C_f = \left(\frac{1}{X}\frac{\partial^2\psi}{\partial Y^2}\right) = f_{YY}(0) = -\delta d \quad (22)$$

$$Nu = \left(-\frac{1}{X}\frac{\partial\theta}{\partial Y}\right) = -\lambda {f_1}'(0) = \lambda\delta \quad (23)$$

Using these results, we discuss the characteristics of some special parameters.

3. Results and Discussion

The present paper demonstrates the Newtonian flow of a fluid with radiation and inclined MHD. Al_2O_3-Cu-H_2O hybrid nanofluid is also considered to obtain new results. The flow is caused due to the linearly stretching vertical plate and the flow is mixed convective in nature. The given PDEs of the form are transformed into ODEs with the help of similarity transformations. The resulting ODEs equations are solved analytically to obtain the analytical solution. A unique class of heat transfer fluid called hybrid nanofluid was developed through technical innovation to improve the efficiency of heat transmission for numerous industrial and engineering applications. In comparison to base fluid and regular nanofluid, hybrid nanofluid may provide a higher thermal efficiency. In many technological applications, including automobile cooling systems, power generation, microelectronics, heat exchangers, and air conditioning, thermal system efficiency optimization is essential. The impact of different parameters can be observed by using graphical arrangements. The results of C_f and Nu values are taken into account. Upper branch solution (ubs) and lower branch solution (lbs) are examined. Today, improving heat transmission is a major issue in engineering and industrial applications. While cooling liquids with low thermal conductivity, such as water, ethylene glycol, and oil, are frequently utilized as pure fluids in industrial applications, the improvement in heat transfer is constrained.

Figure 2a,b portray the impact of $f(Y)$ as a function of Y for varying the Ra_s values for suction and injection cases, respectively. Here, the plots related to $f(Y)$ raises for raising Ra_s values for both $V_C > 0$ and $V_C < 0$ cases. Figure 3a,b represents the effect of $f(Y)$ verses Y for varying the ϕ_1 values. Here, the plots related to $f(Y)$ raises for raising the ϕ_1 values for both $V_C > 0$ and $V_C < 0$ cases. That is the boundary layer thickness is increased due to the increased ϕ_1 values for both $V_C > 0$ and $V_C < 0$.

Figure 4a,b represent the impact of $f_Y(Y)$ as a function of Y for varying the Ra_s values for both $V_C > 0$ and $V_C < 0$ cases, respectively. Here, the axial velocity is incresed for increasing Ra_s values for both $V_C > 0$ and $V_C < 0$ cases.

The C_f verses Pr for varying the λ values is indicated in Figure 5, dual nature is observed in Figure 5, one is ubs and another one is lbs. Here, it is observed that λ value decreases with increasing of C_f for lbs and λ value increases with increases of C_f for ubs. Further, it is seen that Pr value raises for larger λ values.

The impact of Nu on Ra_s for varying the values of λ is indicated in Figure 6, dual nature is observed in Figure 6, one is ubs and another one is lbs; it is observed that λ value decreases with increases of Nu for lbs and λ value increases with increases of Nu for ubs. In addition, it is seen that Ra_s value decreases with increases of λ.

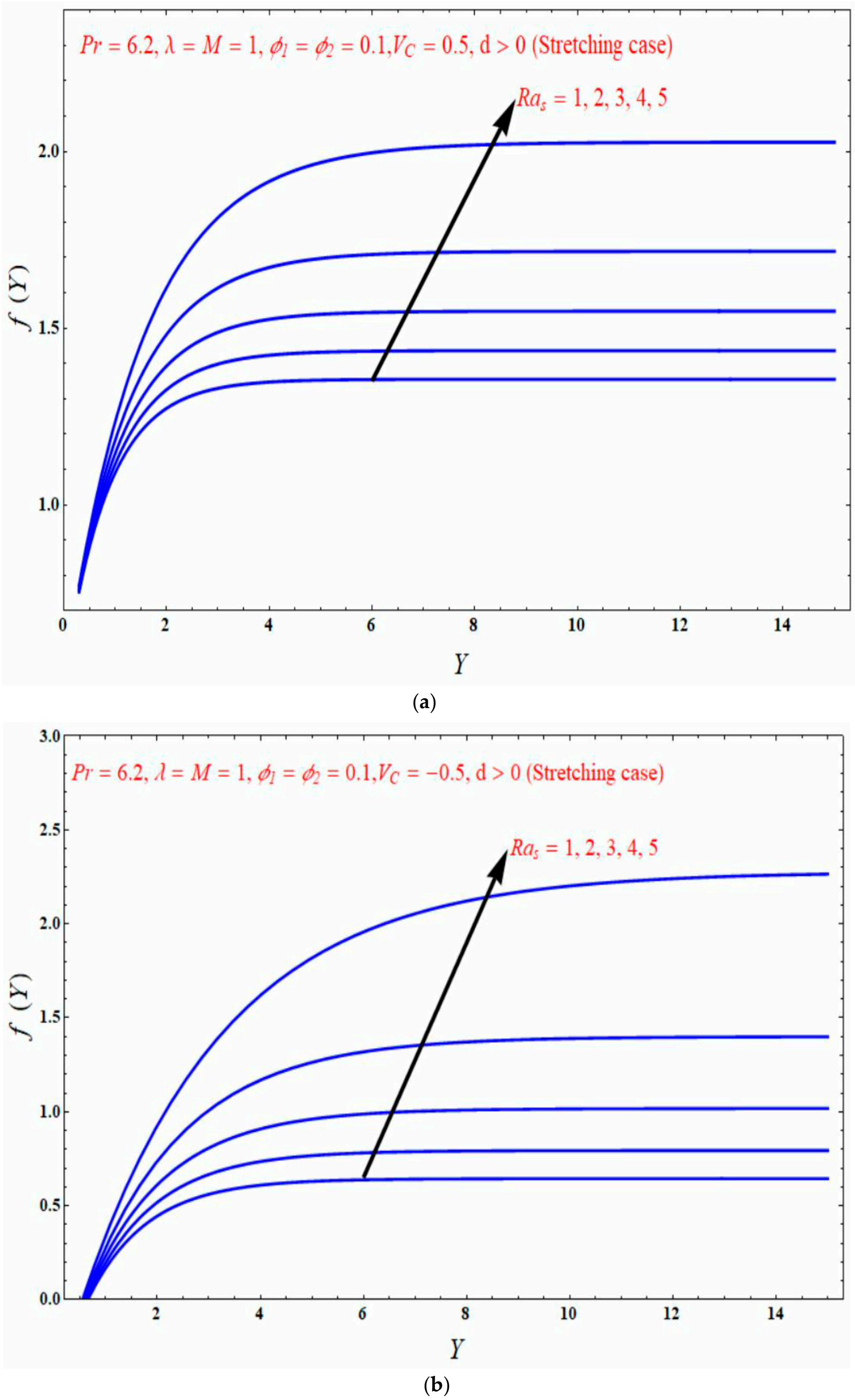
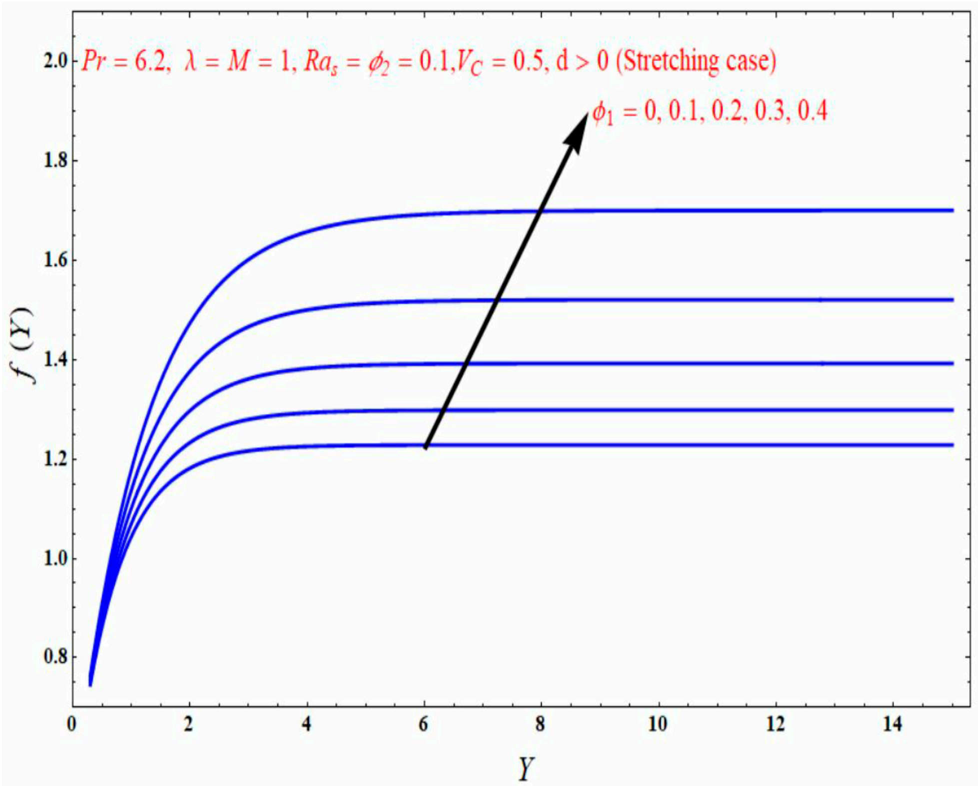
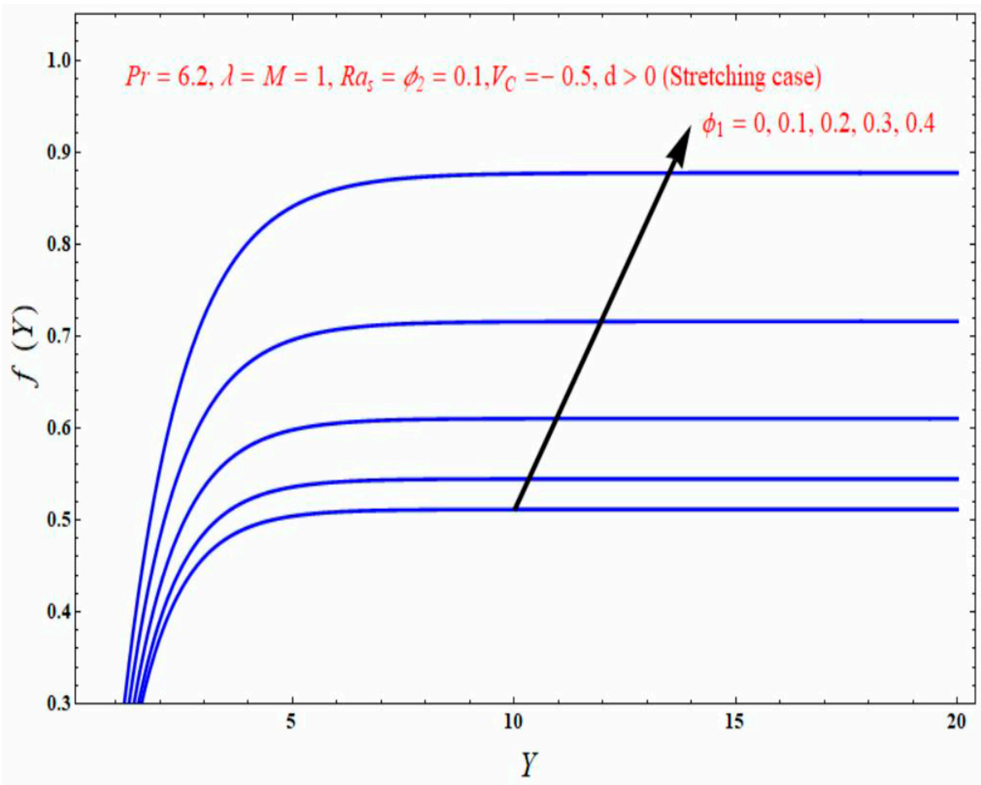


Figure 2. (**a**,**b**): $f(Y)$ verses Y for different Ra_s values at (**a**) $V_C > 0$ and (**b**) $V_C < 0$.



(**a**)



(**b**)

Figure 3. (**a**,**b**): $f(Y)$ verses Y for different ϕ_1 values at (**a**) $V_C > 0$ and (**b**) $V_C < 0$.

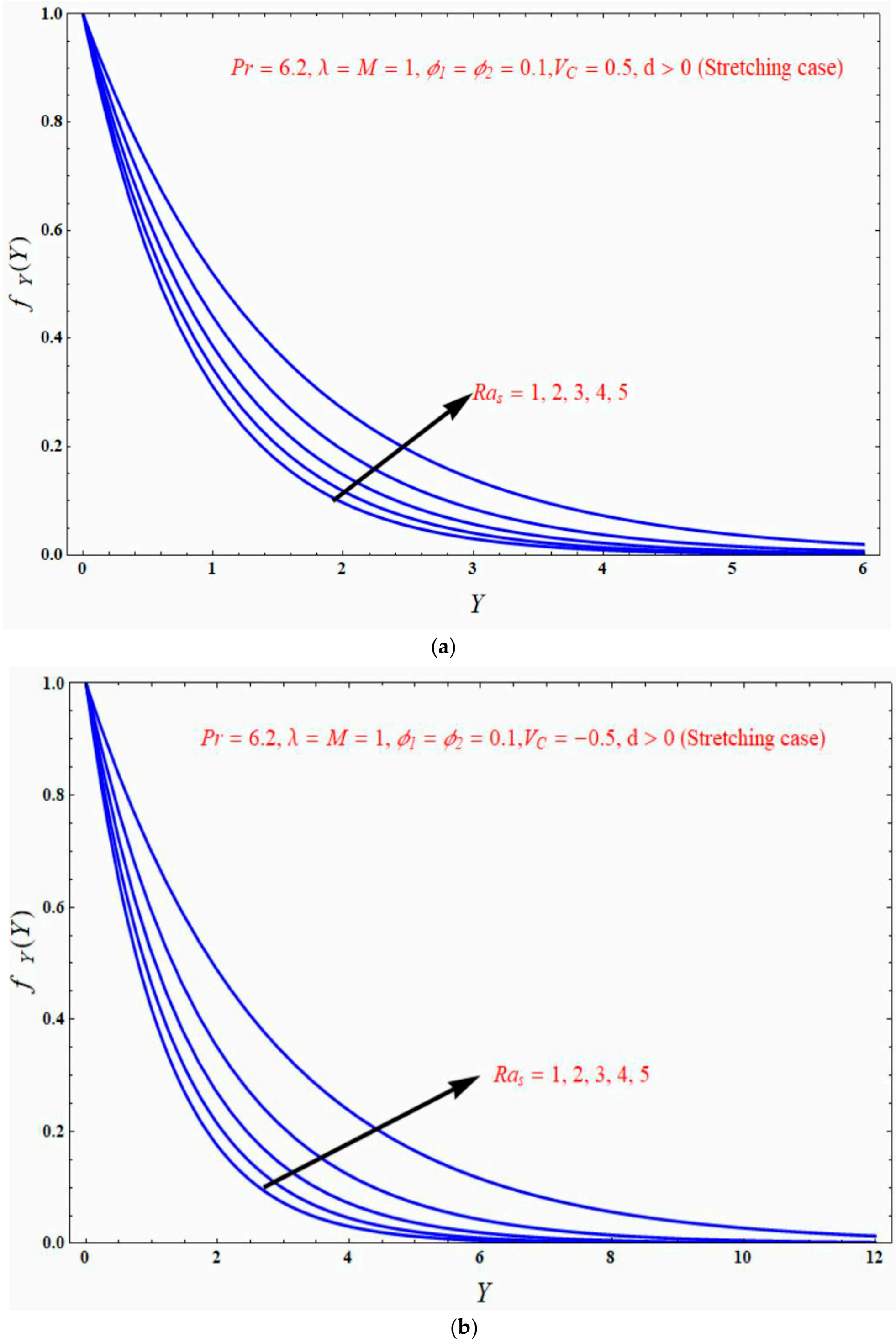


Figure 4. (**a**,**b**): $f_Y(Y)$ verses Y for different Ra_s values at (**a**) $V_C > 0$ and (**b**) $V_C < 0$.

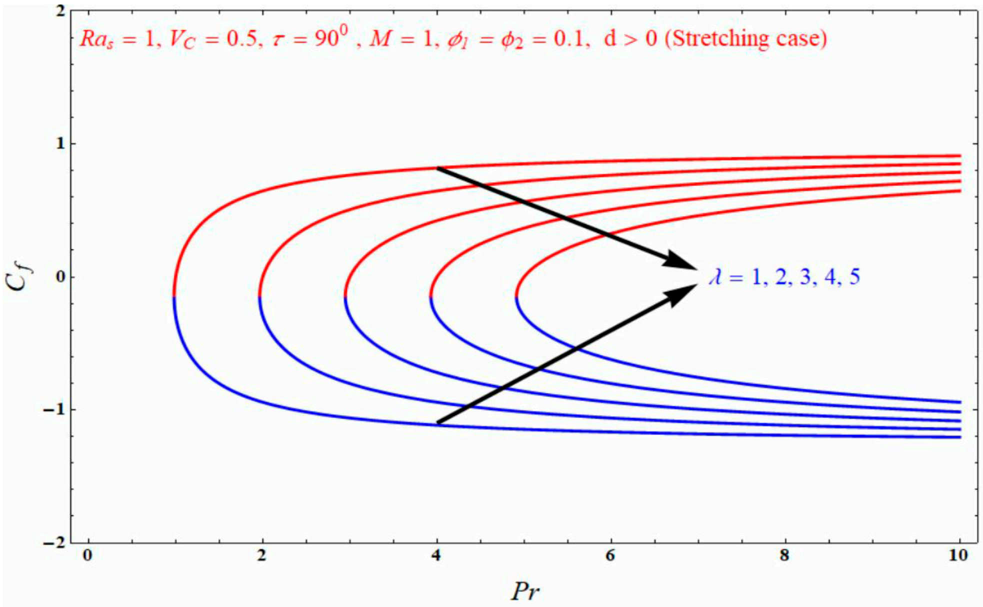


Figure 5. The impact of C_f on Pr for different λ values.

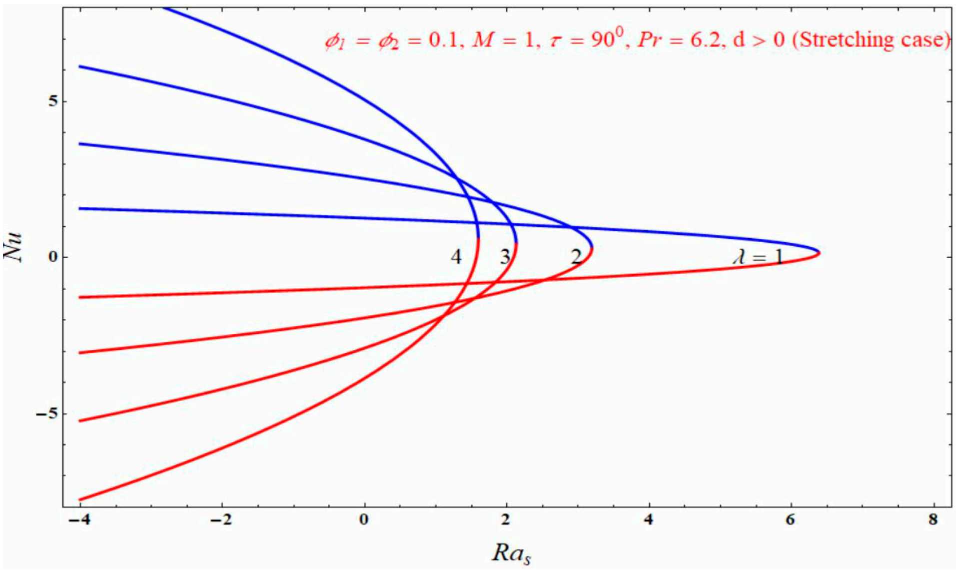


Figure 6. The impact of Nu on Ra_s for different λ values.

4. Concluding Remarks

Al_2O_3-Cu/H_2O hybrid nanofluid is used in the current analysis to improve the heat transfer analysis. The study of inclined magnetohydrodynamics (MHD) mixed convective incompressible flow of a fluid with hybrid nanoparticles contains a colloidal combination of nanofluids and base fluid. The energy equation also includes the impact of radiation. The primary research methodology is first transforming the equations provided by the problem into a non-dimensional form before obtaining them as ordinary differential equations (ODEs). The provided ODEs are then solved using the momentum and transfer equation solutions to yield the equation's root. The main goal entails solving the resulting equations analytically with the aid of appropriate boundary conditions. The yielded ODEs solved exactly to get the proper results. Several physical parameters, such as the stretched/shrinked-Rayleigh number, the stretching/shrinking parameter, the Prandtl number, etc., can be used to discuss the results.

- $f_Y(Y)$ is more for more Ra_s values for both $V_C > 0$ and $V_C < 0$.

- $f(Y)$ is more for more values of Ra_s, and ϕ_1 for both $V_C > 0$ and $V_C < 0$.
- Pr value increases with increases of λ.
- Ra_s value decreases with increases of λ.
- Dual nature is observed.
- The present study helps to motivate the future researchers to conduct the investigations on stretching sheet problems with the help of mixed convective flow with hybrid nanofluid.

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Nomenclature

Symbol	**Description**	**S.I. Unit**
d	Coefficient of stretching/shrinking parameter	$(-)$
$f(Y)$	Dimensionless transverse velocity	$(-)$
$f_Y(Y)$	Dimensionless tangential velocity	$(-)$
$\vec{g}$	Gravity	(N)
k^*	Coefficient of mean absorption	$(-)$
K	Permeability parameter	(m^2)
T	Temperature	(K)
V_C	Mass transpiration	$(-)$
Greek symbols		
α	Dimensional stretching/shrinking parameter	$(-)$
β	Thermal expansion coefficient	(K^{-1})
χ	Thermal diffusivity	(m^2s^{-1})
λ	Dimensional stretching/shrinking parameter	$(-)$
θ	Temperature profile	$(-)$
ν	Kinematic viscosity	(m^2s^{-1})
ρ	Density	(kgm^{-3})
μ	Dynamic viscosity of nanofluid	($kgm^{-1}s^{-1}$)
σ^*	Stefan–Boltzmann constant	($Wm^{-2}s^{-4}$)
Subscripts		
w	Quantities at wall	$(-)$
∞	Quantities at for stream	$(-)$
f	Fluid	$(-)$
hnf	Hybrid nanofluid	$(-)$
Abbreviations		
B. Cs	Boundary conditions	$(-)$
MHD	Magnetohydrodynamics	$(-)$
ODE	Ordinary differential equations	$(-)$
PDE	Partial differential equations	$(-)$

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