Research Article

Insights of Heat and Mass Transfer in Magneto-Mixed Convective Sisko Nanofluid over a Wedge with Viscous Dissipation

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The current analysis provides the important insights of Sisko nanofluid flow over a wedge with thermal radiation and viscous dissipation effects. The Buongiorno nanofluid model, which includes Brownian movement and thermophoresis, is taken into consideration. Momentum, temperature, and nanoparticle concentration equations are used to simulate the current problem. The suitable similarity variables are applied to the governing partial differential equations (PDEs) which yield the dimensionless ordinary differential equations (ODEs). The MATLAB function bvp4c has been used to resolve the resulting ODEs. The attributes of various flow parameters on the transfer rate of mass, heat, temperature, velocity, and nanoparticle concentration have been explored. The pressure gradient parameter boosts the mass transfer and velocity. Moreover, mixed convection leads to the decrement in thermal and nanoparticle concentration boundary layer. The obtained numerical findings are compared to published results in the literature by considering the particular cases to validate the current study and are seen to be in perfect accord.

1. Introduction

In aerodynamics, geothermal systems, and many other fields, convective flow across a wedge has been discussed extensively. The flow over a wedge is significant because each wedge angle generates a distinct pressure profile, providing insight into boundary layer behavior in a variety of conditions. Skan [1] was the first to propose a flow arrangement on the wedge. Since then, many researchers have investigated wedge and produced several useful discoveries, including Yih [2], Sattar [3], Turkylmazoglu [4], Raju and Sandeep [5], Kudenatti et al. [6], Awaludin et al. [7], and many others. Khan and Pop [8] investigated the problem of steady boundary layer flow of nanofluid past a stretchy wedge. For solving the governing system, they employed the implicit finite-difference technique. Rajagopal et al. [9] extended the problem of flow field across a wedge to the problem of non-Newtonian fluid, where fluid of a second grade is examined. Many more studies of the flow field across a wedge were then investigated [10–12]. The steady 2D magnetohydrodynamic wedge flow of micropolar fluid in the presence of fluctuating wall temperature was explored by Ishaq et al. [13]. The boundary layer flows particularly for non-Newtonian fluids over stretched surfaces have been widely discussed by the researchers [14–18]. The Sisko fluid model [19] is one of the most essential models among non-Newtonian fluid models since it accurately describes a few non-Newtonian fluids. It may be assessed as a broad view of Newtonian and power-law fluids. Dadhich and Jain [20] examined some important characteristics of the fluid flow over an exponential surface in the Sisko model. The Falkner–Skan wedge flow of a power-law fluid through a porous material was studied by several researchers, including Kim [21]. Munir et al. [22] investigated convective heat transfer in Sisko nanofluid past a wedge. They applied the unique similarity transformations for converting the physical system. The boundary layer flow of a power-law fluid past a porous stretching wedge was studied by Postelnicu and Pop [23]. Das et al. [24] investigated how different fluid characteristics affect nanofluid flow over a wedge. The flow study was done with the effect of surface slip in account. The wedge flow of a power-law fluid in a porous medium was analyzed by Hassanien et al. [25]. Khan and Shahzad [26] explored Sisko fluid’s Falkner–Skan boundary layer movement.
Bano et al. [27] used analytical methods to investigate the stretching wedge of Casson fluid with varied effects.

Enhancement of heat transfer is essential in improving performances and compactness of electronic devices. Usual cooling agents (water, oil, etc.) have relatively small thermal conductivities, and therefore heat transfer is not very efficient. Thus, to augment thermal characteristics, very small size particles (nanoparticles) were added to fluids forming the so-called nanofluids. These suspensions of nanoparticles in fluids have physical and chemical properties depending on the concentration and the shape of particles. It is observed that adding a little amount of nanoparticles to a base fluid increases the thermal conductivity of the fluid significantly. Loganathan et al. [28] investigated 3D flow of viscoelastic nanofluid over a bidirectional stretched surface. They applied the homotopy analysis method and concluded that heat as well as mass transportation is significantly affected by Brownian motion and thermophoresis. Wikafi et al. [29] examined the impact of heat and mass transfer mechanisms on convective motion near a heated extending sheet embedded horizontally in a bi-phasic medium containing a certain volume fraction of alumina nanoparticles (Al₂O₃) dispersed completely in a micropolar fluidic medium containing 60% ethylene glycol (C₂H₆O₂) (C₂H₆O₂ EG) and 40% pure water (H₂O). Ashraf et al. [30], using the extended differential quadrature approach, quantitatively investigated the peristaltic flow of a blood-based nanofluid. After completing the thorough literature review, the authors observed that no attempt has been made to fully comprehend the transportation of heat and mass in the Sisko model with suspended nanoparticles over a wedge including viscous dissipation effect. Bhatti and Abdelsalam [31] investigated the peristaltically driven movement of Carreau fluid in a symmetric channel under the effect of a generated and applied magnetic field. They used the tantalum (Ta) and gold (Au) nanoparticles in the hybrid nanofluid with thermal radiation effects. Lubrication theory is used to complete the mathematical framework.

High-temperature plasmas, glass manufacturing, and liquid metal fluids all benefit from heat transfer analysis of boundary layer flow with radiation. These transport phenomena difficulties are particularly non-linear when linked with thermal convection processes. Thermal radiation alters the temperature distribution in the boundary layer at high temperatures, which impacts heat transfer at the wall. Multi-physical radiative-convective fluxes have been the subject of a number of research studies [32–35].

The purpose of this analysis is to examine the magneto-mixed convective Sisko nanofluid over a wedge with viscous dissipation. We extended Sisko nanofluid over a wedge from Macha et al. [36]. But we introduce new similarity variables [22, 26] for constructing a mathematical model. The governing partial differential equations are changed into non-linear ordinary differential equations, which are numerically solved by applying MATLAB bvp4c solver. The obtained numerical findings are compared to published results in the literature by considering the particular cases to validate the current study and are seen to be in perfect accord. The current issue has not yet been published in the scientific literature, and it is important to polymeric manufacturing processes and nuclear waste simulations, to the best of the authors’ knowledge.

2. Flow Analysis

In the presence of heat source, radiated laminar flow of Sisko nanofluid is investigated. Heat and mass transport phenomena are considered and discussed. The flow is steady and two-dimensional as illustrated in Figure 1. Rectangular coordinate system is used, where x-axis and y-axis are aligned alongside and perpendicular to wedge surface, respectively. Free stream velocity is considered as \( u_\infty \) where \( u_\infty(\chi) = P \chi^m \) (\( P \) is a positive constant). The wedge angle \( \Omega = \pi \beta_1 \) where \( \beta_1 = 2m/m + 1 \). Besides, it is assumed that temperature \( T \) and nanoparticle fraction \( C \) take constant values \( T_w \) and \( C_w \), respectively, on the surface of wedge. The ambient temperature and concentration are denoted by \( T_{\infty} \) and \( C_{\infty} \), respectively. A uniform magnetic field \( B_0 \) is imposed transverse to the wedge surface.

Based on these assumptions, equations for conservation of mass, momentum, thermal energy, and nanoparticle concentration for Sisko nanofluids can be stated as [12, 18, 20]

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

\[
\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = u_\infty, \quad \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} = 0,
\]

\[
\rho \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial p}{\partial y} + \frac{\partial q}{\partial x}, \tag{2}
\]

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \frac{k}{(\rho C_p)_f} \frac{\partial^2 T}{\partial y^2} + \left[ D_h \frac{\partial C}{\partial y} + \frac{D_T}{T_{\infty}} \left( \frac{T}{T_{\infty}} \right)^2 \right],
\]

\[
\frac{\partial T}{\partial x} + \frac{\partial C}{\partial y} = \frac{\partial^2 T}{\partial y^2} + \frac{\sigma B_0^2 \mu^2}{(\rho C_p)_f} \left( \frac{\partial u}{\partial y} \right)^2 + \frac{\mu}{(\rho C_p)_f} \left( \frac{\partial^2 u}{\partial y^2} \right) + \frac{Q}{(\rho C_p)_f} \left( T - T_{\infty} \right) + \frac{1}{(\rho C_p)_f} \frac{\partial q}{\partial y} + \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \tag{3}
\]

\[
u \frac{\partial C}{\partial x} + \frac{\partial C}{\partial y} = D_h \frac{\partial^2 C}{\partial y^2} + \frac{D_T}{T_{\infty}} \frac{\partial^2 T}{\partial y^2}. \tag{4}
\]
The boundary conditions are
\[ y = 0: \quad u = 0; \quad v = 0; \quad T = T_w; \quad C = C_w, \]  
(5)
\[ y \to \infty: \quad u = u_\infty = Px^m, \quad v \to 0, \quad T \to T_\infty, \quad C \to C_\infty. \]  
(6)

Here, \( \epsilon_1, \epsilon_2, \) and \( n (> 0) \) are material constants; \( \alpha_f = k/\rho C_p \) is the thermal diffusivity; \( \theta \) is the kinematic viscosity; \( C_p \) is the specific heat of the fluid; \( k \) is the thermal conductivity; \( \tau = (\rho C_p)_f/ (\rho C_p)_b \) is the proportion of the heat capacity of nanoparticles to that of the base fluid; \( D_B \) is the Brownian diffusion; \( D_T \) is the thermophoretic diffusion; and \( q_r \) is the radiative heat flux.

The following non-dimensional variables are proposed [22, 26]:
\[
\eta = \frac{Y}{x} (Re_y)^{1/(n+1)},
\]
\[
u = u_{\infty} f' (\eta),
\]
\[
\theta(\eta) = \frac{T - T_{\infty}}{T_w - T_{\infty}},
\]
\[
\phi(\eta) = \frac{C_w - C_{\infty}}{C_{\infty} - C_w}.
\]

The Rosseland diffusion flux model can be defined as follows:
\[
q_r = -\frac{4\alpha^*}{3k^*} \frac{\partial T^4}{\partial y}.
\]

Usually, \( T^4 \) is expressed as a linear function of temperature, and applying Taylor’s expansion (ignoring higher-order terms), it takes the form
\[
T^4 = 4T_{\infty}^4 - 3T_{\infty}^4.
\]

The following set of ODEs may be obtained by using (7), (8), and (9) in equations (2)–(6):
\[
Af''' + n(-f^n) m - 1 f''' + Mf' - m f'^2 + (m + 1)f f'''
+ m + \lambda[\theta + N\phi] \sin \left(\frac{\alpha}{2}\right) = 0,
\]
\[
\left(1 + \frac{4R}{3}\right) \theta' + P_r [(m + 1) f' \theta' + N_r \theta' \phi' + N_r \theta'^2] + \delta P R \theta
+ M P_r E_t f'^2 + E_r f''^2 = 0,
\]
\[
\phi'' + P \frac{E_t}{N_r} (m + 1) f' \phi' + \left(\frac{N_r}{N_r}\right) \phi' = 0.
\]

Transformed boundary conditions are
\[
\text{at } \eta = 0: f(\eta) = 0, f'(\eta) = 0, \theta(\eta) = 1, \phi(\eta) = 1,
\]
\[
\text{at } \eta \rightarrow \infty: f'(\eta) = 1, f(\eta) = 1, \theta(\eta) = 0, \phi(\eta) = 0.
\]

Here prime implies the differentiation with respect to \( \eta \), and the non-dimensional terms are described as
\[
M = \frac{\delta B_{EC} x}{\rho u_{\infty}}, P_r = \frac{\theta}{\sigma_f}, N_t = \frac{rD_{m}(C_{w} - C_{\infty})}{\theta},
\]
\[
N_l = \frac{rD_{f}(T_w - T_{\infty})}{\theta}, L_e = \frac{\alpha L_e}{D_{m}}, Re_{a} = \frac{\rho x u_{\infty}}{\epsilon_2},
\]
\[
R_s = \frac{\rho x (u_{\infty})^2 \epsilon_2}{\epsilon_2}, A = \left(\frac{Re_{a}}{Re_{a}}\right)^{\frac{1}{2}}.
\]

2.1. Coefficients of Heat and Mass Transport. The main goal of this study is to figure out what factors are important to engineers when they deal with heat and nanoparticle mass transfer. The engineering interests of the physical quantities are defined below: local Nusselt number \( N_u = \frac{q_{w}}{k(T_w - T_{\infty})} \), and local nanofluid Sherwood number is given by \( S_h = \frac{x q_{w}}{D_{m}(C_w - C_{\infty})} \) where \( q_{w} = -k(\partial T/\partial y)_{y=0} \) is wall heat flux. Using above-mentioned transformations, these
parameters will reduce to 
$$(\text{Re}_b)^{-1/(n+1)} \quad \eta_{\text{cs}} = -(1 + 4R/3)\theta'(0)$$ and 
$$(\text{Re}_b)^{-1/(n+1)} \phi'_{\text{cs}} = -\phi'(0).$$

### 3. Numerical Computation

The above-mentioned system of non-linear ODEs along with boundary conditions is solved by applying MATLAB bvp4c code. Thus, the system is converted to first-order ODEs using the mathematical algorithm which is appended below ((13)–(29)). "Boundary conditions defined at infinity are addressed by fixing it at a finite value, for example, $\eta_{\text{cs}} = 10$ implies that variable is confined in $0 \leq \eta \leq 10^n$. Calculations are performed numerically using an interval $\Delta \eta = 0.01, 10^{-3}$ is a convergent criterion to repeated and attain the numeric solution.

\begin{align}
 f &= g_1, \quad (13) \\
 f' &= g_2, \quad (14) \\
 f'' &= g_3, \quad (15) \\
 f''' &= g_3, \quad (16)
\end{align}
\[ \theta = g_4, \]
\[ \theta' = g_5, \]
\[ \theta'' = g_6, \]
\[ \phi = g_6, \]
\[ \phi' = g_7, \]
\[ \phi'' = g_9, \]
\[ f''' = \frac{g_2^2 m - M g_2 - m - (m + 1) g_1 g_3 - \lambda [g_4 + N g_6] \sin(\Omega/2)}{A + (-1)^{n-1} n (g_3)^{n-1}}, \]
\[ \theta'' = g_5' = \frac{P_r (m + 1) g_1 g_5 + \delta P_r g_4 + E_c (g_3)^2 + M P_r E_c g_3^3 + P_r \left( N_b g_5 + N_t g_3 \right)}{(1 + 4R/3)} \]  

\[ \phi'' = \tilde{g}_7' = \left[ P_r \epsilon (m + 1) g_1 g_7 + \frac{N_t}{N_b} g_3 \right]. \]  

Using boundary conditions:

\[ g_0 (1) = 0, g_0 (2) = 0, g_0 (4) - 1 = 0, g_0 (6) - 1 = 0, \]  

\[ g_1 (2) - 1 = 0, g_1 (1) - 1 = 0, g_1 (4) = 0, g_1 (6) = 0. \]
4. Result and Discussion

In this section, the impact of numerous physical parameters on temperature and concentration is demonstrated. The fixed values of physical parameters are \( m = 1, M = 0.8, n = 1, R = 0.1, Ec = 0.2, \lambda = 1, N = 0.1, Nb = 0.5, Le = 1, A = 1, N = 0.1 \). These findings are summarized in Figures 2–17 and Tables 1 and 2. Figures 2(a) and 2(b) illustrate the graphs of temperature \( (\theta) \) and concentration \( (\phi) \) for different \( M \). As strength of magnetic field is increased, it increases resistive force. Therefore, additional heat is produced which causes high temperature and concentration of nanoparticles decreases. The impact of \( m \) on fluid flow and heat is represented by Figures 3(a) and 3(b). This variation is due to \( m \), which is associated with pressure gradient. Increasing values of \( m \) indicate a promising pressure gradient which improves the flow. Fluid temperature is also influenced by wedge angle. Figures 4(a) and 4(b) demonstrate the effect of \( A \) (material parameter) on \( \theta \) and \( \phi \). Due to the fact that the material parameter has an inverse relationship with consistency index \( b \) (fluid’s viscosity). As \( A \) increases, fluid viscosity decreases which causes less resistance for the fluid.

![Figure 11](image1.png)

**Figure 11:** (a) \( \theta \) vs \( R \). (b) \( \phi \) vs \( R \).

![Figure 12](image2.png)

**Figure 12:** (a) \( \theta \) Vs \( \lambda \). (b) \( \phi \) Vs \( \lambda \).
to move, and this increases the fluid velocity. As a result, an increase in material parameter $A$ results in a decay of the temperature profile and an increase in concentration.

Figures 5(a) and 5(b) illustrate the influence of $Pr$ on the distribution of heat and nanoparticle concentrations, respectively. The graph demonstrates that when $Pr$ grows, the temperature of the fluid drops. Since $Pr$ is inversely proportional to thermal diffusivity. Consequently, the temperature drops and the nanoparticle concentration is also reduced as $Pr$ rises. Figure 5(c) and 5(d) depict the effect of $Ec$ on $\theta$ and $\phi$. Growing $Ec$ enhances the temperature of fluid. As energy is accumulated in fluid due to frictional heating, nanoparticle concentration decreases. Figures 6(a) and 6(b) illustrate $N_t$ on $\theta$ and $\phi$. Growing $N_t$ causes particles to move more quickly, raising the fluid temperature. Furthermore, when $N_t$ increases, the nanoparticle concentration nearest to the surface drops and rises away from it. As $N_t$ increases, more particles are expelled off the heated surface, causing the concentration to increase. Additionally, as seen in Figures 8(a) and 8(b), the parameter $N_p$ has an effect on the concentration of nanoparticles. With increasing $N_p$ values, the concentration of nanoparticles in fluid falls.

Figure 9 shows a shift in concentration as $Le$ increases. Evidently, $\phi$ reduces as $Le$ increases. This is because $Le$ has an inverse relationship with $D_y$, which is associated with $N_p$. Thus, an increase in $Le$ lowers the thermal diffusivity, causing a decrease in the speed in boundary layer area. Figures 10(a) and 10(b) illustrate temperature and concentration patterns for different $\delta$ (which is $>0$).
enhancing $\delta$, the temperature scales are increased but reduction is observed in concentration values. Consequently, the concentration decreases. A similar trend is observed for temperature and concentration when $R$ increases as shown in Figures 11(a) and 11(b). High values of $R$ result in a higher temperature of fluid.

Figures 12(a) and 12(b) indicate temperature and concentration profiles with different $\lambda$. Clearly, it is concluded that increment in $\lambda$ causes the decline in fluid’s temperature and similar behaviour is observed for the concentration.

Likewise, the increasing values of $N$ reduce both temperature and concentration as depicted in Figures 13(a) and 13(b). Figure 14 shows that increment in $L_c$ causes decay in concentration profile. Hence, nanofluid’s Sherwood number $-\varphi'(0)$ is enhanced. Instead, Figure 15 reveals that the nanofluid’s Sherwood number decreases with $N_t$. Also, Figure 16 shows the diminishing tendency of local Nusselt number as $Ec$ and $M$ increase. Figures 17(a) and 17(b) show that heat and mass transfer rates increase as $m$ increases. Increasing $\delta$ values cause a decrease in heat transfer while mass transfer increases.

Table 1 compares the local skin friction and Nusselt number for different $m$, and it is pretty evident that the conclusions of the current analysis are consistent with those of other researchers. Table 2 shows the variation of heat and mass transfer rate with respect to change in $m$, $N$, $Pr$, $\lambda$, and $\delta$. It is perceived that heat transfer rate shows an increasing behaviour when the values of all the parameters are rising; however, when $\delta$ is increasing, the heat transfer rate is decreasing. Also, the rate of mass transfer enhances with the increase of the value of $m$.

![Figure 16: Change in $-\theta'(0)$ with $M$ and $Ec$.](image1)

![Figure 17: (a) 3D plot of $(Re_b)^{-1/(n+1)}Sh_x$ for $m$ and $\delta$. (b) 3D plot of $(Re_b)^{-1/(n+1)}Nux$ for $m$ and $\delta$.](image2)
Table 2: $Nu_x$ and $Sh_x$ for various values of $m, N, Pr, \lambda$, and $\delta$ taking $n = 1.2$, $M = 0.5$, $Ec = 0.2$, $R = 0.1$, and $A = 1$.

<table>
<thead>
<tr>
<th>$m$</th>
<th>$N$</th>
<th>$Pr$</th>
<th>$\lambda$</th>
<th>$\delta$</th>
<th>$(Re_a)^{-1/(n+1)} Nux$</th>
<th>$(Re_a)^{-1/(n+1)} Shx$</th>
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5. Conclusion

In the present work, analysis of heat and mass transfer in the Sisko model with suspended nanoparticles over a wedge including viscous dissipation effect is investigated. The effects of the wedge angle parameter, nanoparticle volume fraction, radiation, heat generation/absorption, and other variables are explored and presented graphically. For many physical parameters, numerical values of rate of heat and mass transport are provided, and noteworthy aspects are explained in depth. The obtained numerical findings are compared to published results in the literature by considering the particular cases to validate the current study and are seen to be in perfect accord. The following is a summary of the key findings of this study:

(i) The higher values of pressure gradient parameter ($m$) lead to the rising phenomena in the velocity profile.

(ii) While a material parameter ($A$) is increased, the temperature profile decays and the concentration rises.

(iii) Prandtl and Schmidt numbers affect mass concentration reversely.

(iv) Thermal and solutal boundary layers are declined due to the augmentation in mixed convection parameter ($\lambda$).

(v) Increasing values of magnetic field and Eckert number will produce a diminishing behaviour in heat transfer rate.

(vi) Mass transfer rate is more pronounced for higher values of pressure gradient parameter.

Abbreviations

- $A$: Material parameter (dimensionless)
- $B_0$: Magnetic field strength ($kg s^{-2}A^{-1}$)
- $C$: Concentration ($kg m^{-3}$)

$C_{co}$: Ambient concentration ($kg m^{-3}$)

$C_w$: Sheet concentration ($kg m^{-3}$)

$c_{sp}$: Specific heat ($J kg^{-1} K^{-1}$)

$D_B$: Coefficient of Brownian diffusion ($m^2 s^{-1}$)

$D_p$: Coefficient of thermophoretic diffusion ($m^2 s^{-1}$)

$E_c$: Eckert number (dimensionless)

$k$: Thermal conductivity ($W m^{-1} K^{-1}$)

$L_c$: Lewis parameter (dimensionless)

$m$: Pressure gradient parameter

$M$: Magnetic field parameter (dimensionless)

$N$: Concentration to thermal buoyancy ratio parameter

$N_B$: Brownian diffusion parameter (dimensionless)

$N_i$: Thermophoresis parameter (dimensionless)

$Nu_x$: Local Nusselt number (dimensionless)

$P_r$: Prandtl number (dimensionless)

$q_r$: Radiative heat flux ($W m^{-2}$)

$R$: Radiation parameter (dimensionless)

$Re_a$: Local Reynolds numbers (dimensionless)

$Re_B$: Sherwood number (dimensionless)

$T$: Fluid temperature (K)

$T_w$: Sheet temperature (K)

$T_{w0}$: Ambient fluid temperature (K)

$u, v$: Velocity components ($m s^{-1}$)

$x, y$: Cartesian coordinates (m)

$G_r$: Local Grashof number (dimensionless)

$\alpha_f$: Thermal diffusivity ($m^2 s^{-1}$)

$\beta$: Coefficient of thermal expansion ($K^{-1}$)

$\beta_e$: Coefficient of concentration expansion

$\delta$: Wedge angle parameter

$\delta$: Heat source/sink parameter (dimensionless)

$\eta$: Similarity parameter (dimensionless)

$\theta$: Temperature similarity function (dimensionless)

$\phi$: Concentration similarity function (dimensionless)

$\lambda$: Mixed convection parameter (dimensionless)

$\tau$: Ratio of the effective heat capacity

$\sigma$: Electrical conductivity ($S m$)

$f$: Fluid phase

$\omega$: Surface condition.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors’ Contributions

All authors contributed equally to this work. All authors have read and approved the final version of the manuscript.
References


