RESEARCH ARTICLE

Thermophoresis and suction/injection roles on free convective MHD flow of Ag–kerosene oil nanofluid

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Abstract

In this article, the mass and heat transfer flow of Ag–kerosene oil nanofluid over a cone under the effects of suction/injection, magnetic field, thermophoresis, Brownian diffusion, and Ohmic-viscous dissipation was examined. On applying the suitable transformation, PDEs directing the flow of nanofluid were molded to dimensionless ODEs. The solution of the reduced boundary value problem was accomplished by applying Runge–Kutta–Fehlberg method via shooting scheme and the upshots were sketched and interpreted. The values of shear stress and coefficients of heat and mass transfer were attained for some selected values of governing factors. The obtained results showed that when the amount of surface mass flux shifts from injection to the suction domain, the heat and mass transfer rate grew uniformly. However, they have regularly condensed with the rise in the magnitude of the magnetic field and particle volume fraction. Several researches have been done using cone-shaped geometry under the influence of various factors affecting the fluid flow, yet, there exists no such investigation that incorporated the response of viscous-Ohmic dissipation, heat absorption/generation, suction/blowing, Brownian diffusion, and thermophoresis on the hydro-magnetic flow of silver-kerosene oil nanofluid over a cone.

Keywords: mass transfer; Ohmic-viscous dissipation; silver-kerosene oil nanofluid; suction/injection; thermophoresis

Nomenclature

| Symbol | Definition |
|--------|------------|
| \( B(x) \) | Non-uniform magnetic field(\(T\)) |
| \( B_0 \) | Magnetic field strength(\(T\)) |
| \( C \) | Concentration (\(Kg/m^3\)) |
| \( C_p \) | Specific heat capacity at constant pressure (\(J/KgK\)) |
| \( D_b \) | Brownian diffusion coefficient |
| \( E \) | Viscosity variation parameter |
| \( E_c \) | Eckert number |
| \( f \) | Non-dimensional stream function |
| \( g \) | Acceleration due to gravity(\(m/s^2\)) |
| \( Gr \) | Local Grashof number |
| \( K \) | Thermophoretic coefficient |
| \( k \) | Thermal conductivity(\(W/mK\)) |
| \( Le \) | Lewis number |
| \( M \) | Magnetic field parameter |
| \( N_c \) | Concentration ratio |
| \( N_t \) | Temperature ratio parameter |
| \( N_{Nu} \) | Local Nusselt number |
| \( Pr \) | Prandtl number |
| \( Q_{H} \) | Heat generation/absorption coefficient |
| \( Q \) | Heat generation/absorption parameter |
| \( r \) | Radius of the base of a cone(\(m\)) |
| \( S \) | Suction/injection parameter |
| \( S_{Sh} \) | Local Sherwood number |
| \( T \) | Temperature(\(K\)) |
| \( (u, v) \) | Velocity along x and y direction(\(m/s\)) |
| \( V_T \) | Thermophoretic velocity |
| \( (x, y) \) | Cartesian coordinates(\(m\)) |

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Greek symbols
\( \beta_T \): Volumetric thermal expansion (K\(^{-1}\))
\( \Phi \): Non-dimensional concentration
\( \phi \): Nanoparticle volume fraction
\( \rho \): Density (kg/m\(^3\))
\( \mu \): Dynamic viscosity (Ns/m\(^2\))
\( \mu_\infty \): Ambient viscosity of the fluid
\( \nu \): Kinematic viscosity (m/s)
\( \eta \): Non-dimensional direction
\( \sigma_f \): Electrical conductivity (S/m)
\( \psi \): Stream function
\( \theta \): Non-dimensional temperature (K)
\( \omega \): Constant
\( \delta \): Semi-vertical angle

Subscripts
\( f \): Base fluid
\( p \): Solid fluid
\( nf \): Nanofluid
\( w \): Wall
\( \infty \): Ambient condition

Superscript
\( \cdot \): Derivative with respect to \( \eta \)

1. Introduction
The colonization of colloidal particles in a solution responds to a macroscopic temperature gradient, known as thermophoresis. Thermophoresis often applies to aerosol mixtures (fog, dust, geyser steam, smoke, and haze) and has numerous applications like thermal precipitator, optical fiber, nuclear reactor, and obstructing the deposition of a small particle on electronic chips. Due to its growing applications in the engineering field, it has earned much importance. Due to these applications, Loganathan and Arasu (2010) explored the consequences of thermophoresis and injection/suction on the non-Darcy flow of fluid past a wedge in the presence of the magnetic field. Hady, Ibrahim, Abdel-Gaied, and Eid (2011) considered the effect of heat sink/source to inspect the behavior of the natural convective flow of nanofluid through a cone. Research of Rawat, Pandey, and Kumar (2018) accounts for the consequence of slip, Brownian motion, and thermophoresis to investigate the boundary layer flow of Cu-H\(_2\)O nanofluid. Sheremet, Roşca, Roşca, and Pop (2018) studied the nature of nanofluid, streaming into a porous cavity affected by thermophoresis and suction/injection. Recently, Ullah, Alzahrani, Shah, Ayaz, and Islam (2019) applied Reiner–Philippoff fluid model to scrutinize the nanofluid flow past a stretching surface under the impact of thermophoresis and pedesis. Bondareva, Sheremet, Oztop, and Abu-Hamdeh (2018a) examined the role of thermophoresis, Brownian diffusion, and local heater on the convective flow of nanofluid through a triangular cavity. Some of the recent investigations dealing with the effect of thermophoresis were reported by Sheremet, Gimpean, and Pop (2017), Astanina, Abu-Nada, and Sheremet (2018), Bondareva, Sheremet, Oztop, and Abu-Hamdeh (2018b), and Ali et al. (2019).

Convection or convective heat transfer is the process in which heat transfer occurs from one space to another due to the movement of the fluid. It is a pooled process of advection and conduction. Researchers have a keen interest in convection, owing to its great significance in the engineering and industrial field. Rashad, Chamkha, and El-Kabeir (2011) illustrated how the mass fraction affects the convective flow of fluid over a sphere in a non-Darcian porous medium. The unsteady flow of nanofluid over cone or plate due to porous medium and natural convection was discussed by Buddakkargri and Kumar (2015). Dinavind and Pop (2017) employed the Keller Box and Homotopy Analysis Method to achieve the upshots of relevant factors of free convective nanofluid flow past a cone. Some of the essential contributions in this direction were elaborated by Chamkha, Al-Mudhaf, and Pop (2006), Gorla and Chamkha (2011), Sheikholeslami, Shehzad, and Li (2018), Alkanhal et al. (2019), and Sheikholeslami, Shah, Shafee, Khan, and Tili (2019).

Suction/injection was generally used in those models that were closed. It is a force that is used to draw the fluid into an interior space. Pop and Watanabe (1992) carried out a theoretical analysis with the main aim to discuss the influence of injection/suction on fluid flowing over a cone with free convection and heat flux. The authors used the Differential Method to solve the existing equation describing the flow. Kumar and Nath (2009) considered the natural convective flow of the fluid past a cone filled with a porous medium due to suction/injection. Cheng (2015) investigated the influences of suction and temperature-dependent viscosity on heat transfer convective flow past a cone with varying wall temperature in the porous medium. Raju, Kumar, Varma, Madaki, and Prasad (2018) applied the Cattaneo–Christov heat flux model to scrutinize the flow and heat transfer behavior of fluid in the presence of the magnetic field, suction/injection, and heat generation/consumption. Some of the recent investigations accounting the impact of injection/suction to explore the behavior of fluid flow past a stretching sheet were done by Mohammadnejad, Raslan, Abdel-Wahed, and Abdel-Aal (2018), Pandey and Kumar (2018a), and Rehman, Idrees, Shah, and Khan (2019).

MHD (magnetohydrodynamics) has widespread applications such as in Geophysics, electronics, astrophysics (e.g. sunspots are caused by the sun’s magnetic fields, solar field), aerospace engineering (e.g. MHD sensors), cooling of nuclear reactors, and drug targeting. Jawad et al. (2019) recognized the unsteady hydro-magnetic flow of SWCNTs-based nanofluid to examine the effect of viscous dissipation and thermal radiation on heat transfer and entropy generation. Kannan, Pullupu, and Shehzad (2019) explored the convective flow of nanofluid induced by a cone, and they employed the Crank–Nicholson approach for solving the non-dimensional ODEs describing the flow of fluid. Some of the investigations on hydro-magnetic flow of nanofluid were addressed by Bondareva, Sheremet, and Pop (2015), Singh, Pandey, and Kumar (2016), Pandey and Kumar (2018), Ahmad et al. (2019), Kalpana, Madhura, Iyengar, and Uma (2019), Khan, Hayat, Waqs, Alsaedi, and Khan (2019), Shah et al. (2019), Upreti and Kumar (2019), and Vo, Shah, Sheikholeslami, Shafee, and Nguyen (2019).

The recent growth of progressive technologies has motivated interest in fluid flow through a cone. It has applications in various disciplines like aeronautical engineering, astrophysics, hydrology, solar collectors, dental applications, and many more. Gorla, Krishnan, and Pop (1994) inspected the natural convective flow of fluid over a frustum of the cone in the presence of heat flux conditions. They found that amplification in the buoyancy factor augments the Nusselt and Sherwood number. Using the cone-shaped geometry, researchers (Chamkha (2001), Takhar, Chamkha, and Nath (2003), Chamkha, and Abu-Hamdeh (2018a) examined the role of thermophoresis, pedesis. Bondareva, Sheremet, Oztop, and Abu-Hamdeh (2018a) examined the role of thermophoresis, Brownian diffusion, and local heater on the convective flow of nanofluid through a triangular cavity. Some of the recent investigations dealing with the effect of thermophoresis were reported by Sheremet, Gimpean, and Pop (2017), Astanina, Abu-Nada, and Sheremet (2018), Bondareva, Sheremet, Oztop, and Abu-Hamdeh (2018b), and Ali et al. (2019).

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Abbasbandy, Rashad, and Vajravelu (2013), RamReddy, Murthy, Chamkha, and Rashad (2013), and Ghalambaz, Behseresht, Behseresht, and Chamkha (2015) investigated the effects of numerous factors, like MHD, radiation, and nanoparticle volume fraction, on free/forced convective steady/unsteady flow of nanofluid. The role of uneven heat sink/source on the hydro-magnetic flow of the Cattaneo–Christov fluid past a cone and a wedge was studied by Kumar, Reddy, Sugunamma, and Sandeep (2018). In this analysis, they concluded that the heat transfer rate is more for nanofluid flow over a cone rather than a wedge. Very recently, Saleem, Firdous, Nadeem, and Khan (2019) inspected the transient flow of Walter’s B nanofluid about a rotating cone. The notion of this analysis is to discuss the consequences of thermophoresis, buoyancy, random motion, and magnetic field.

With the motivation from all the above-cited work, the current study titled “Thermophoresis and suction/injection roles on free convective MHD flow of Ag–kerosene oil nanofluid” elucidates the behavior of nanofluid flow and heat and mass transfer. The equations describing the flow of fluid through cone were reduced into non-linear DEs, and these DEs are solved using the Runge–Kutta–Fehlberg (RKF) fourth- and fifth-order technique through shooting scheme. Numerical solutions for various governing parameters are acquired and described in detailed graphically.

2. Problem Statement

Let’s consider 2D, steady, incompressible and hydro-magnetic flow of nanofluid that passes through a cone under the influence of viscous-Ohmic dissipation, suction/injection, thermophoresis, and heat generation/absorption. Let the semi-vertical angle of the vertical cone be \( \delta \) and its base radius be \( r = x \sin \delta \). The origin was shifted toward the vertex of the geometry (cone). The directions of the horizontal and vertical axes are \( (x, y) \), and they signify that the horizontal direction depicts the cone surface, and the vertical axis is at a right angle to it. The intensity of the magnetic field applied on the flow direction is \( B(x) = B_0 x/\sqrt{Gr} \), and the gravity \( (g) \) is acting against the flow as revealed in Fig. 1. Again, assume that the temperature of the wall near and far away from the cone is denoted by \( T_w \) and \( T_\infty \), respectively. In case \( (T_w - T_\infty) > 0 \), the wall of cone is heated, while surface is cooled when \( (T_w - T_\infty) < 0 \); the fluid is moving with the velocity \( u_w = (v/x)(Gr)^{1/2} \). Further, presume that the fluid viscosity is varied with temperature, and it was classified as \( \mu_f = \mu_f(\theta) \), (see Raju, Sandeep, & Malvandi, 2016), where \( \omega \) is the constant and \( \mu_f \) signifies the ambient viscosity of the fluid and the stream function \( \psi \) can be defined as \( (u, v) = (\frac{\psi_y}{\mu_f}, -\frac{\psi_x}{\mu_f}) \).

Based on the above-mentioned assumptions, the fundamental equations for the nanofluid flow within the boundary layer near the vertical cone can be represented as (Khan & Sultan, 2015)

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

\[
u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{1}{\mu_f} \left[ \mu_f \frac{\partial^2 u}{\partial y^2} + g(\rho\beta) \frac{\partial T}{\partial y} \cos(\delta) - \sigma_f B(\chi) x u \right]
\]  

\[
(\rho C_p) \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \kappa_f \frac{\partial^2 T}{\partial y^2} - Q_B(T - T_\infty) + \mu_f \left( \frac{\partial v}{\partial y} \right)^2 + \sigma_f B(\chi)^2 u^2
\]  

where \( V_r = -\frac{B_0}{\sqrt{Gr}} \) is the thermophoretic velocity and \( K \) is the thermophoretic coefficient.

Here, \( x \) and \( y \) are the components of velocity in the horizontal and vertical directions, i.e. along the \( x \) and \( y \) axes, \( C \) and \( T \) are the concentration and temperature of species, respectively, electrical conductivity of the base fluid (\( = \sigma_f \)), strength of the magnetic field (\( = B_0 \)), coefficient of heat generation/absorption (\( = Q_B \)), and the coefficient of Brownian diffusion (\( = D_B \)).

The boundary conditions for the present study are as follows:

\[
u = v = 0, \quad T = T_w, \quad C = C_w \quad \text{as} \quad y = 0;
\]

\[
u = 0, \quad T \to T_\infty, \quad C \to C_\infty \quad \text{at} \quad y \to \infty.
\]  

To transform the existing non-linear PDEs into non-linear ODEs, the following similarity transformations are applied (see Khan & Sultan, 2015):

\[
u = \frac{\nu}{\sqrt{Gr}} (Gr)^{0.5} f(\eta), \quad v = \frac{\nu}{\sqrt{Gr}} (Gr)^{0.25} \left( \frac{1}{2} f'(\eta) - \frac{1}{2} f(\eta) \right),
\]

\[
\psi = x v \sin(\delta) (Gr)^{0.25} f(\eta), \quad \eta = \frac{x}{\sqrt{Gr}} (Gr)^{0.25},
\]

\[
T = T_\infty + (T_w - T_\infty) \eta(\eta),
\]

\[
Gr = \frac{\sigma_f^2 \rho_s (T_\infty - T_w) \cos(\delta)}{\nu_f}, \quad C = C_\infty + (C_w - C_\infty) \Phi(\eta)
\]  

The relations between physical quantities like viscosity (\( \mu \)), density (\( \rho \)), thermal expansion coefficient due to temperature difference (\( \alpha(\theta) \)), thermal conductivity (\( k \)), and the heat capacity (\( C_p \)) of nanofluid in the form of conventional fluid are formulated as (Oztop & Abu-Nada, 2008; Upcert, Pandey, & Kumar, 2018)

\[
\mu_f = \frac{\mu}{(1-\phi)^{2.5}}, \quad \rho_f = (1-\phi) + \phi \frac{\rho_s}{\rho_f}, \quad \frac{\alpha_f}{\alpha_f(\theta)} = (1-\phi) + \phi \frac{\alpha_s}{\alpha_f(\theta)}, \quad \frac{k_f}{k_f(\theta)} = (1-\phi) + 2\phi \frac{k_s}{k_f(\theta)};
\]  

\[
\frac{\rho C_p}{\rho C_p(\theta)} = (1-\phi) + \phi \frac{\rho C_p_s}{\rho C_p(\theta)} + \frac{k_f}{k_f(\theta)} \frac{\rho C_p(\theta)}{k_f(\theta)} - \frac{\rho C_p_s}{\rho C_p(\theta)}.
\]  

Here, the suffixes \( nf \), \( p \), and \( f \) represent the nanofluid, the solid nanoparticle, and the base fluid, respectively.
Now, employing the above relations in equations (2)–(4), the transformed ODEs of the flow including dimensionless parameters are as follows:

\[
(1 + E\theta^{-1}(1 - \phi)^{-2}) f''' - 0.5 \left( f f'' - f'(1 - \phi + \frac{\phi}{\phi_1}) - M f' \right)
\]

\[
-(1 + E\theta^{-1}(1 - \phi)^{-2}) E f'\theta' + \left( f(1 - \phi) + \frac{\phi}{\phi_1}\right) \theta = 0
\]

(8)

\[
\frac{\nu_k}{\nu} \Phi_1 \theta'' + 0.5 Pr \left( f(1 - \phi) + \frac{\nu_C K}{\rho K_1} \right) f \theta' - Q \theta + ME C Pr f^2
\]

\[
+ (1 + E\theta^{-1}(1 - \phi)^{-2}) Ec Pr f^2 = 0
\]

(9)

\[
\Phi'' + 0.5 Le f \Phi' - \frac{K Le}{Nt + \theta} \left( \frac{\left( Nc + \Phi \right) \nu'' + \theta' \Phi'}{(Nt + \theta)\alpha^2} \right) = 0
\]

(10)

with the modified boundary conditions:

\[
f'(\eta_0) = 0, \quad f(\eta_\infty) = S, \quad \theta'(\eta_0) = 1, \quad \Phi(\eta_0) = 1.
\]

(11)

3. Numerical Method

The equations (3)–(4) are describing the momentum, energy, and mass transfer characteristics of Ag–kerosene oil nanofluid, respectively. In order to solve these equations, first we have to reduce them into ODEs and then the preliminary boundary conditions are to be transformed. This task can be accomplished by employing similarity transformation defined in equation (6). Now, the obtained non-linear ODEs along with new boundary conditions are solved via RKF scheme with shooting procedure. During the whole computation, the step size is \( \eta = 0.001 \), whereas the value of \( \eta_m \) is elected in such a way that the boundary conditions are gratified asymptotically. Now assume that \( m_1 = f, m_2 = f', m_3 = \theta, m_4 = \theta', m_5 = \Phi, \) and \( m_6 = \Phi' \).

Using the above substitution, the following system of equations is obtained:

\[
\begin{bmatrix}
    m_1 \\
    m_2 \\
    m_3 \\
    m_4 \\
    m_5 \\
    m_6
\end{bmatrix} =
\begin{bmatrix}
    m_2 \\
    m_3 \\
    m_4 \\
    m_5 \\
    m_6 \\
    m_6
\end{bmatrix}
\]

(14)

\[
\begin{bmatrix}
    A_0 A_3 \left[ 0.5 (m_1 m_2 - m_1 m_4) A_1 + M m_2 + \frac{1}{(2 \phi_1 \phi_0)} E n m_3 - A_3 m_4 \right] \\
    \frac{k r}{\nu} \left[-0.5 Pr A_3 m_1 m_5 + Q m_4 - M E C Pr m_2 - \frac{1}{(2 \phi_1 \phi_0)} E C Pr m_3 \right] \\
    -0.5 Le m_1 m_7 + \frac{K Le}{Nt} \left[ Nc + m_3 \right] \theta' + m_5 - \frac{Nc + m_3}{(Nt + \theta)\alpha^2} m_5 m_6
\end{bmatrix}
\]

\[
\begin{bmatrix}
    m_1 \\
    m_2 \\
    m_3 \\
    m_4 \\
    m_5 \\
    m_6
\end{bmatrix} =
\begin{bmatrix}
    m_2 \\
    m_3 \\
    m_4 \\
    m_5 \\
    m_6 \\
    m_6
\end{bmatrix}
\]

and auxiliary initial conditions are as follows:

\[
\begin{bmatrix}
m_1 \\
m_2 \\
m_3 \\
m_4 \\
m_5 \\
m_6
\end{bmatrix} = \left[ S \ 0 \ \alpha_1 \ 1 \ \alpha_2 \ \alpha_3 \right]^T.
\]

(15)

4. Results and Discussion

The computation has been done for studying the effect of dimensionless controlling parameters such as Prandtl number (Pr), magnetic field parameter (M), injection/suction parameter (S), Eckert number (Ec), temperature ratio parameter (Nt), concentration ratio parameter (Nc), Lewis number (Le), thermophoretic coefficient (K), and particle volume fraction (\( \phi \)) on flow, thermal, and concentration field profiles for Ag–kerosene oil nanofluid. The upshots have been shown with the help of tables and figures. The characteristics of fluid and nanoparticle has been shown in Table 1. The value of M is varied from 0.2 to 2.5, Pr varied from 4 to 6.72, Ec ranges from 0.1 to 1.5, Nt extended from 0.1 to 4.0, Nc fluctuated from 0.1 to 3.5, K varied from 0.1 to 2.0, particle volume fraction ranges from 0.02 to 2.0, S lies between \(-1.5 \leq S \leq 2 \), and the values of Lewis number lie between \([0.24, 1.2] \). Also, the computation was preceded for physical quantities such as friction factor, local Nusselt number, and local Sherwood number. To validate the numerical outcomes of \( f'(0) \) and \( \theta'(0) \) in the current study, they were compared with previous literature under some special cases. Table 2 exhibits an excellent concord with earlier published literature. Also, the results of the concentration profiles are contrasted with those stated by Khan and Pop (2010) when \( Nc = 0.1 = Nt = Pr = 10 \). This comparison showed an outstanding conformity, which is clear from Fig. 2a and b. It was noticed from Fig. 2a and b that with rise in the magnitude of Le, the concentration profiles declined as well as the corresponding boundary layer became narrow.

The profiles of Ag–kerosene oil nanofluid for \( f'(\eta), \theta'(\eta), \) and \( \Phi(\eta) \) are represented through Figs 3–19. These graphs showed that the boundary conditions held true to all the values and asymptotically tend to zero; it supports the accuracy of acquired results. Figures 3–5 show the influence of Prandtl number on velocity, temperature, and concentration fields when \( M = 0.8, Ec = 0.3, Q = 0.1, Le = 0.5, K = 0.2, E = 1, \) and \( Nt = 0.1 = Nc \). Figure 3 exhibits that velocity and the corresponding boundary layer thickness decline continuously with escalating values of Pr. Figure 4 illustrates that the boundary layer thickness of the temperature profile is inversely related to Pr. This is because with the rise in Pr, the thermal diffusivity of the fluid declines and as a result, the thickness of the thermal boundary layer depreciates. Figure 5 exhibits that the concentration profiles for Ag–kerosene oil nanofluid grows from \( 0 \leq \eta \leq 2 \) as Pr grows and then it increased in the rest of the domain. Figure 6 shows the response of temperature ratio parameter (Nt) on the concentration profile when \( Pr = 6.72, Q = 0.02, E = Le = M = 1, K = Nc = 0.1, Ec = 0.3, S = 0.5, \) and \( \phi = 0.2 \). From the figure, it is concluded that concentration profile of Ag–kerosene oil nanofluid grows with growing values of Nt. Moreover, the thickness of concentration boundary layer becomes wider with Nt. The variation in distribution of concentration of the nanofluid due to the cause of several values of pertinent parameter Nc is portrayed in Fig. 7 for \( Pr = 6.72, Q = 0.02, E = Le = M = 1, K = 0.1, Ec = 0.3, Nt = 0.2, S = 0.5, \) and \( \phi = 0.2 \). Thus, we observed that the width of concentration...
Table 1: Characteristics of fluid and nanoparticle were given by Raju, Sandeep, and Malvandi (2016).

| Fluid          | ρ (Kg m⁻³) | Cₚ (K g⁻¹ K⁻¹) | k (Wm⁻¹ K⁻¹) | β × 10⁻³ (K⁻¹) | μ (Ns m⁻²) | σ (Sm⁻¹) |
|----------------|------------|----------------|--------------|----------------|------------|-----------|
| Kerosene oil   | 783        | 2090           | 0.15         | 21             | 0.00164    | 5 × 10⁻¹¹  |
| Silver (Ag)    | 10 500     | 235            | 429          | 1.89           | 6.3 × 10⁷   |

Table 2: Comparison of numerical values of $f''(0)$ and $-θ'(0)$ when $K = M = Nc = Nt = 0 = Q = φ$.

| Pr  | Pătrulescu, Groșan, and Pop (2014) | Raju, Sandeep, and Malvandi (2016) | Present study |
|-----|-----------------------------------|-----------------------------------|---------------|
|     | $f''(0)$                          | $-θ'(0)$                          | $f''(0)$      | $-θ'(0)$      | $f''(0)$ | $-θ'(0)$ |
| 0.733 | 1.1505 | 0.5158 | 1.1505 | 0.5158 | 1.1505 | 0.5158 |
| 6.700 | 1.1505 | 1.1025 | 1.1505 | 1.1026 | 1.1505 | 1.1026 |

Figure 2: Comparison of $θ(η)$ (Present result-(a) with Khan and Pop (2010)-(b)).

Figure 3: Influence of $Pr$ on $f′(η)$.

boundary frequently depreciated with increase in $Nc$. Figure 8 exhibits the influence of thermophoretic coefficient ($K$) on concentration profile due to the fixed value of rest of relevant parameters such as $Pr = 6.72$, $Q = 0.02$, $E = Le = M = 1$, $K = 0.1$, $Ec = Nc = 0.3$, $Nt = 0.2$, $S = 0.5$, and $ϕ = 0.2$. On viewing these outlines, we point out that with increase in thermophoretic coefficient $K$, the concentration of nanofluid regularly decelerates and satisfies the transformed boundary conditions in the domain. The graph between $η$ versus concentration function $Φ(η)$ was plotted for the selected values of Lewis number ($Le$), when $Pr = 6.72$, $Q = 0.02$, $E = M = 1$, $K = 0.2 = Nt = ϕ$, $Ec = Nc = 0.3$, and $S = 0.5$, and has been displayed in Fig. 9. As we focus on these outlines, it is confirmed that each curve has asymptotic
behavior in the range of $0 \leq \eta \leq 40$. It means that concentration profile of nanofluid declines as $Le$ grows.

The influence of $Ec$ on velocity, temperature, and concentration field has been shown in Figs 10–12. Figure 10 declares that the velocity augments from the wall and achieves a peak value at $\eta = 0.6$ and then onwards, it gets reduced in the rest of the domain. Additionally, as $Ec$ increases, temperature profile becomes predominant near the cone, while far from the surface, temperature outlines constantly go down and asymptotically tend to zero. Moreover, the velocity boundary layer thickness elevates with an escalation in $Ec$. Figure 11 exhibits that temperature outlines rise with Eckert number in the domain of $0 \leq \eta \leq 4$ and...
the thickness of thermal boundary layer was lifted along with it. On seeing Fig. 12, we observed that the concentration profiles of the nanofluid decline with augmentation in the parameter Ec in the range of $2 \leq \eta \leq 8$; still, there is no deviation between these curves near the wall of the cone or in the region of $0 \leq \eta < 2$.

The influences of magnetic field parameter $M$, when $Pr = 6.72$, $Q = 0.2$, $E = Le = 1$, $K = Nt = \phi = 0.2$, $Ec = Nc = 0.1$, and $S = 0.5$, on the flow, thermal, and concentration field profile have been portrayed in Figs 13–15. Figure 13 shows that the velocity profile increases rapidly and attains maximum value at $\eta = 0.5$; after this point, the velocity dropped down in the remaining region. However, throughout the whole domain the velocity of nanofluid predominantly rises with an enhancement in $M$. On viewing Figs 14 and 15, curves of the thermal and concentration fields are accelerated, as the magnetic field parameter escalates. This happened due to the generation of an opposing force to the flow; such a force is known as Lorentz force. The profile of physical quantities, for instance, Nusselt and Sherwood numbers, has been reported in Figs 16–19. The combined effect of the magnetic field and nanoparticle volume fraction parameter on Nusselt and Sherwood numbers has been shown in Figs 16 and 17, for $Pr = 6.72$, $Q = 0.2$, $E = Le = 1$, $K = Nt = \phi = 0.2$, $Ec = Nc = 0.1$, and $S = 0.5$. It has been observed from Fig. 16 that the coefficient of heat transfer rate slows down continuously on escalating the values of $M$ and $\phi$. Similarly, the same trends are achieved for the mass transfer rate from Fig. 17. Figures 18 and 19 illustrate the variation in the outlines of Nusselt number and mass transfer due to the simultaneous effects of suction/blowing parameter and volume fraction of nanoparticles, when $Pr = 6.72$, $E = 2$, $K = Nt = 0.2 = Nc = Q$, $Ec = Le = 0.5$, and $M = 1$. Figure 18 de-
Figure 16: Influence of $M$ and $\phi$ on Nusselt number.

Figure 17: Influence of $M$ and $\phi$ on Sherwood number.

Figure 18: Influence of $S$ and $\phi$ on Nusselt number.

Figure 19: Influence of $S$ and $\phi$ on Sherwood number.

picts that, on moving from injection to suction domain together with $\phi$, the heat transfer rate increases near the wall and decreases on moving away from the surface of the cone. Also, we can say that the rate of heat transfer is an accelerating function of $\phi$ in injection region, while it is a non-increasing function of $\phi$ in the suction region. Figure 19 indicates the outlines of the rate of mass transfer coefficient, which is similar to the profiles of Nusselt number. It means that mass transfer rate augments in the injection area and decreases in the suction region when amplification in the volume fraction parameter was done. It is remarkable to notice that in the absence of suction/injection, there is no change in the profiles $-\theta'(0)$ and $-\Phi'(0)$.

Table 3 illustrates the effect of several dimensionless parameters on the flow behavior of the nanofluid. From this table, it can be stated that the magnitude of shear stress, heat and mass transfer rate depreciates with increase in the magnitude of $M$. The heat and mass transfer coefficients are augmented together with Prandtl number, while reverse trends were attained for increasing values of Eckert number. The skin friction coefficient amplifies with Eckert number while it diminishes with an increase in Prandtl number. The pertinent parameters like Le, Nt, Nc, and K do not have any significant impact on $f'(0)$ and $-\theta'(0)$. Table 4 describes the variation in mass and heat transfer coefficients due to the simultaneous effect of magnetic field parameter and volume fraction parameter. On viewing this table, we noticed that, for a constant magnetic field, $-\theta'(0)$ and $-\Phi'(0)$ regularly decrease with increasing particle volume fraction. Table 5 elucidates the variation in numerical values of $-\theta'(0)$ and $-\Phi'(0)$ with suction/injection parameter $S$ and particle volume fraction parameter $\phi$. It is clear from this table that when the mass flux parameter value shifts from injection to suction region for a particular value of $\phi$, both the dimensionless terms Nusselt and Sherwood numbers are enhanced.

5. Conclusions

In the current study, authors investigative the combined influence of viscous-Ohmic dissipation, injection/suction, thermophoresis, Brownian diffusion, and heat generation/absorption on free convective MHD flow of silver-kerosene oil nanofluid over a cone. The significant features of the present investigation are as follows:

- With the increase in magnetic field parameter, temperature and concentration distribution escalated but heat and mass transfer rates were depreciated.
- On accelerating temperature ratio parameter, concentration profile of nanofluid augments, but mass transfer coefficient depreciated.
- The profile of local Nusselt and Sherwood numbers first increased in injection region, but in suction area, both decelerated regularly, when amplification in solid particle volume fraction was done.
Table 3: Calculated values of skin friction coefficient, Nusselt number, and Sherwood number for several values of relevant parameters when $S = 0.5$.

| Pr  | Q   | M   | Le  | Nc  | Nd  | Ec  | E   | K   | $\phi$ | $f^{\prime}(0)$ | $-\theta^{\prime}(0)$ | $-\Phi^{\prime}(0)$ |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|-----------------|---------------------|-----------------------|
| 6.72 | 0.02 | 1.0 | 1.0 | 0.1 | 0.1 | 0.3 | 1.0 | 0.1 | 0.2 | 0.57388 | 1.17022 | 0.44247 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.40272 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.36013 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.44325 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.55694 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.73185 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.56932 |
|     |     |     |     |     |     |     |     |     |     |         |         | 1.2903  |
|     |     |     |     |     |     |     |     |     |     |         |         | 2.7767  |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.14693 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.29366 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.66935 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.80272 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.60088 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.30044 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.10017 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.05009 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.02504 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.01252 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.00626 |
|     |     |     |     |     |     |     |     |     |     |         |         | 0.00313 |

Table 4: Calculated values of $-\theta^{\prime}(0)$ and $-\Phi^{\prime}(0)$ for various values of $M$ and $\phi$ when $Pr = 6.72, Q = 0.2, E = Le = 1, K = Nd = 0.2, Ec = Nc = 0.1$, and $S = 0.5$.

| M   | $\phi$ | $-\theta^{\prime}(0)$ | $-\Phi^{\prime}(0)$ | $-\theta^{\prime}(0)$ | $-\Phi^{\prime}(0)$ | $-\theta^{\prime}(0)$ | $-\Phi^{\prime}(0)$ |
|-----|--------|------------------------|----------------------|------------------------|----------------------|------------------------|----------------------|
| 0.02 |        |                        |                      |                        |                      |                        |                      |
| 0.04 |        |                        |                      |                        |                      |                        |                      |
| 0.06 |        |                        |                      |                        |                      |                        |                      |
| 0.2  | 1.83045 | 0.77280                | 1.75567              | 0.759561               | 1.683811             | 0.7 4628               |
| 0.5  | 1.81851 | 0.76734                | 1.74398              | 0.754329               | 1.672930             | 0.74150                |
| 0.8  | 1.80935 | 0.763165               | 1.73490              | 0.750273               | 1.664302             | 0.73770                |
| 1.0  | 1.80426 | 0.760901               | 1.72988              | 0.748025               | 1.659423             | 0.73558                |
| 2.0  | 1.78655 | 0.753030               | 1.71205              | 0.740176               | 1.641984             | 0.72799                |

Table 5: Calculated values of $-\theta^{\prime}(0)$ and $-\Phi^{\prime}(0)$ when $Pr = 6.72, E = 2, K = Nd = 0.2 = Nc = Q, Ec = Le = 0.5$, and $M = 1$.

| S   | $\phi$ | $-\theta^{\prime}(0)$ | $-\Phi^{\prime}(0)$ | $-\theta^{\prime}(0)$ | $-\Phi^{\prime}(0)$ | $-\theta^{\prime}(0)$ | $-\Phi^{\prime}(0)$ |
|-----|--------|------------------------|----------------------|------------------------|----------------------|------------------------|----------------------|
| 0.02 |        |                        |                      |                        |                      |                        |                      |
| 0.04 |        |                        |                      |                        |                      |                        |                      |
| 0.06 |        |                        |                      |                        |                      |                        |                      |
| -1.5 | 0.49659 | 1.71780                | 0.536097             | 1.71975                | 0.57528              | 1.721658               | 0.651302             |
| -1.0 | 0.83103 | 1.79526                | 0.870750             | 1.79765               | 0.90915              | 1.800002               | 0.981500             |
| 0.0  | 2.02742 | 2.00254                | 2.026876             | 2.00250               | 2.02621              | 2.002390               | 2.024562             |
| 1.0  | 4.03627 | 2.29743                | 3.923502             | 2.287891              | 3.81934              | 2.279050               | 3.632500             |
| 2.0  | 6.69270 | 2.67246                | 6.422030             | 2.647928              | 6.17108              | 2.625320               | 5.712620             |

- Due to the augmentation in the magnetic parameter together with nanoparticle volume fraction parameter, heat and mass transfer profile frequently depreciated.
- The momentum boundary layer depreciated with increasing values of Eckert number.

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Conflict of interest statement

Declarations of interest: none.

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