Research Article

Numerical Investigation for Radiative Transport in Magnetized Flow of Nanofluids due to Moving Surface

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In this article, we examined the magnetized flow of ethylene glycol- (50 – 50%) water-based nanoliquids comprising molybdenum disulfide (MoS_2) across a stretching sheet. Flow properties were examined under the impacts of magnetic field and thermal radiation. The behavior of heat generation/absorption is also accounted. Similarity transformations are used on the system of PDEs to get nondimensional ODEs. The obtained nondimensional ODEs are solved with the help of the Runge–Kutta–Fehlberg method via computational software MATHEMATICA. The behavior of prominent parameters for velocity and thermal profiles is plotted graphically and discussed in detail. It is depicted that the temperature field is upgraded with increase in the heat generation/absorption parameter. Furthermore, a larger Schmidt number causes reduction in the concentration field. The current formulated model may be useful in biomedical engineering, biotechnology, nanotechnology, biosensors, crystal growth, plastic industries, and mineral and cleaning oil manufacturing.

1. Introduction

Nanofluids play an essential role in our daily life assisting innovations in industries such as HVAC, electronics, and automotive and mechanical engineering for efficient increase of heat energy of fluids and improving heat transmission in materials. Nanofluids are often characterized when nanoparticles are combined with some regular fluids. The use of a liquid with disseminated particles as a heat-transfer fluid has been around for a long time; nevertheless, owing to sedimentation of the dispersed particles, the traditional scattered fluids cannot be used. Nanofluids do not have the aforementioned drawbacks. The inclusion of nanoparticles (metals or their oxides) in very small-volume fractions significantly increases the heat proficiency of the base fluid. According to the conclusions of the first experiments on nanofluid heat capacity, nanofluids are observed to be heat-transfer fluids that are exceptionally reactive and can be utilized rather than water.

To improve the emphatically viable qualities of one another, an ideal mix of nanoparticles should be chosen.

Keeping this in view, Suresh [1] first and foremost proposed the possibility of using half and half nanofluids to all the more likely improve the critical qualities of normal nanoparticles. An assortment of logical investigation distributions were obtained on the possibility of mixture nanofluids. Momin [2] provided an observational examination of convective and crossover nanoparticles for laminar streaming in tendency cylinders. Crossover nanofluids involve at least two kinds of nanoparticles having new thermophysical and compound aspects that are fit for upgrading power of thermal transportation inferable from synergic sway [3]. Tian et al. [4] discussed 2-D and 3-D executions and their impact on thermal sink viability of the MHD half-breed nanoparticle subject to slip and nonslip streams. Al-Hossainy et al. [5] reviewed the highest order rate of rotating reactants of single nanofluid ($\text{PEG} - \text{H}_2\text{O}/\text{ZrO}_2$) and hybrid nanofluid ($\text{PEG} - \text{H}_2\text{O}/\text{ZrO}_2 + \text{MgO}$) over the stretching surface. Roy et al. [6] assessed the transport of micropolar water-based hybrid nanoliquids through a stretchable surface. Effects of porous circle with powerful properties of stage

alter measure through PCM improved roundabout line all through nanofluid constrained convective in scattering working point is examined by Alizadeh et al. [7]. The outcomes of transport using water-based crossover nanoliquids with heat features were accounted by Fazeli et al. [8]. Kumar et al. [9] explored examination of thermal transport improvement observed because of the impact of significant liquid fluctuation qualities in the presence of radiation on cross-breed nanoliquids. Aziz et al. [10] discussed Powell–Eyring water-based cross-breed transport of nanoliquids with convective heat transmission under volumetric entropy improvement for the consistently flat penetrable extending sheet. Haider et al. [11] examined nanofluid transport in a Darcy–Forchheimer permeable space through a rotating plate. Few studies of hybrid nanoliquids with different geometries are provided in [12–18].

The influence of magnetic field on an electrical current-conductive liquid has an impact on boundary layer transport because of ionization. If the ionized liquid with the lower density is affected by a stronger electromagnetic field, then final conduction of the fluid decreases and, as a result, free-ion spiraling of electromagnetic field lines cause natural current in magnetic and electrical fields. This current is named as “Hall current.” The magnetic field is considered highly important in a variety of nanofluid technologies and industrial applications. Several devices, such as motors, bearings, and magnetohydrodynamic devices, geophysical configurations, and chemical processes are intensely traumatized by the effect of magnetohydrodynamics magnetostrictive physical occurrences of fluids. Magnetohydrodynamics has numerous chemical and industrial manufacturing applications in the related industrial sectors where temperature disruptions exist. Usually, variations can fall below 350 degrees centigrade. Alfven in 1942 firstly proposed the concept of magnetohydrodynamics [19]. Kholshchevnik [20] in the nineteen century employed two combined cathodes in the magnetohydrodynamic generator to observe the impact of boundary current. Zainal et al. [21] noticed magnetohydrodynamic water-based mixture ($\text{Al}_2\text{O}_3/\text{H}_2\text{O}$) nanoliquid transport through a permeable extended/shrunked surface with quadratic velocity. Patil et al. [22] investigated attributes of magnetohydrodynamic Prandtl nanoliquid transport through an extending surface. Elayarani et al. [23] explored the numerical framework for 2-dimensional bioconvective Carreau nanoliquid, incorporating motile microorganisms with the electromagnetic field and slip features. Sabu et al. [24] considered magnetohydrodynamic (MHD) convection ferro-nanofluids (Fe_3O_4 -water) transport through a channel. Saqib et al. [25] discussed MHD transport of a ferro-nanoliquid mixture in presence of radiation. Almakki et al. [26] assessed the magnetohydrodynamic micropolar-nanoliquid transport using an extending sheet. Yasmin et al. [27] developed magnetohydrodynamic Casson nanoliquid transport using the Brinkman framework. Few studies on magnetohydrodynamics (MHD) with hybrid nanoliquids can be seen in [28–34].

Thermal radiation moves at a pace equivalent to that of lighting. Effect of thermal radiation is an important part of the research due to its realistic engineering applications such as furnace construction, glass manufacturing, gas-cooled nuclear power plant construction, polymer manufacturing, and propelled systems. Firstly, Hunt in 1978 presented the concept of generating radiation by utilizing nanoparticles [35]. Siddiqua et al. [36] assessed convection in micropolar nanoliquids in the presence of thermal radiation. Magnetohydrodynamic (MHD) transport of nanoliquids through wedges was presented by Sreedevi et al. [37]. Malek et al. [38] analyzed numerical clarification of Rosseland relation for thermal radiation in improved essential capacities. Gireesha et al. [39] assessed nanomaterials of half and half nanofluid subject to convective conditions. Zainal et al. [40] addressed thermal transport properties of water-based nanoliquids under impacts of MHD and thermal radiation through a permeable moving sheet. Hayat et al. [41] examined the features of thermal radiation on 3-D flow of nanoliquids through carbon nanotubes. Eid et al. [42] explored the gold-blood nanofluid to improve the heat-transfer rate. Rana et al. [43] investigated the thermal radiation effects on nanoliquid flow by adopting the Buongiorno model. Khan et al. [44] investigated the entropy generation aspects on the Williamson nanofluid under the effects of a chemical reaction. Gireesha et al. [39] examined the thermal radiation impacts on hybrid nanoliquids. Khan et al. [45] explored the hybrid nanoliquid with entropy of the system.

Nanoparticles have the ability to expand surface area and thermal efficiency and engage fluid particles with one another in liquids. As a result, this phenomenon is crucial in industrial operations, as well as solar sources of energy and biomedical therapies. A nanofluid has recently been found to be important in a wide range of heat transmission techniques. Generator cooling, refrigeration, and heating in structures, circuit cooling, cooling systems, the coolant in cutting, and the coolant in machining, automotive cooling, and radioactive system cooling are few applications of nanofluids. Numerous researchers were inspired to use nanofluids to solve real-world heat transfer issues as a result of these relevant implementations. Motivated from the above survey of the literature, the novelty of the current study was to obtain the numerical solution of ethylene glycol- (50 – 50%) water-based nanoliquid flow containing molybdenum disulfide (MoS_2) through a stretched sheet. To fulfill this gap in the current analysis, we have considered the magnetized MoS_2 -ethylene glycol- (50 – 50%) water-based nanoliquid with thermal radiation and heat source/sink configured with a stretching sheet. The system of PDEs is reduced to ODEs. The numerical outcomes are found with the Runge–Kutta–Fehlberg method using software MATHEMATICA. The outcomes of velocity, temperature, and concentration according to different variations of the involved parameters are dissected graphically. The effects of nanoparticle volume fraction, thermal radiation, and heat source/sink are valuable characteristics towards the novelty of the accounted model.

2. Mathematical Formulation

Consider the two-dimensional flow of the MoS₂-ethylene glycol- (50 – 50%) water-based nanofluid over a stretching sheet. Let us assume the Cartesian coordinate (x, y) in such a way that x -axis is along the sheet and y -axis is perpendicular to it (see Figure 1). Here, molybdenum disulfide (MoS₂) is used as nanoparticles in ethylene glycol-water (50 – 50%) mixture. The impacts of thermal radiation and heat generation/absorption are considered. Let T_w and C_w be the surface temperature and concentration, respectively. The assumptions of the current analysis are as follows [46, 47]:

- (i) Two-dimensional steady flow of nanofluid is developed
- (ii) The flow is generated through a stretching surface
- (iii) Heat-transfer improvement through MoS₂-ethylene glycol- (50 – 50%) water-based nanofluid is considered
- (iv) Heat absorption/generation and thermal radiation are present

The governing equations are [46, 48]

FIGURE 1: Physical view of the model.

$$\begin{aligned}
 \partial_x u + \partial_y v &= 0, \\
 u \partial_x u + v \partial_y u &= \frac{\mu_{nf}}{\rho_{nf}} \partial_{yy} u - \frac{\sigma_{nf}}{\rho_{nf}} B_0^2 u, \\
 u \partial_x T + v \partial_y T &= \frac{k_{nf}}{(\rho c_p)_{nf}} \partial_{yy} T - \frac{1}{(\rho c_p)_{nf}} \partial_y q_r + \frac{Q_0}{(\rho c_p)_{nf}} (T - T_0), \\
 u \partial_x C + v \partial_y C &= D_m \partial_{yy} C.
 \end{aligned} \tag{1}$$

The boundary conditions are [46, 48]

$$\begin{aligned}
 u = U_w, v = 0, T = T_w = T_0 + Ax^{n+1}, C = C_w = C_0 + Bx^{n+1} \text{ at } y = 0, \\
 u \longrightarrow 0, T \longrightarrow T_0, C \longrightarrow C_0 \text{ as } y \longrightarrow \infty.
 \end{aligned} \tag{2}$$

Here, μ_{nf} denotes the nanofluid dynamic viscosity, ρ_{nf} denotes the density of nanofluid, $(\rho c_p)_{nf}$ denotes the nanofluid specific heat, σ_{nf} denotes the electric conductivity of nanofluid, T denotes the temperature, k_{nf} denotes the

nanofluid thermal conductivity, T_0 denotes the temperature away from the surface, and C_0 denotes the concentration away from the surface.

We considered the following similarity variables [46]:

$$\begin{aligned}
u &= C_1 C_2 x^{(2n+1)/3} f', \\
v &= -\left[\left(\frac{2+n}{3}\right) C_1 x^{\frac{n-1}{3}} f + C_1 \xi x^{\frac{n-1}{3}} f'\right], \\
\theta(\eta) &= \frac{T - T_0}{A x^{n+1}}, \\
g(\eta) &= \frac{C - C_0}{B x^{n+1}}, \\
\xi &= C_2 x^{\frac{n-1}{3}} y, \\
C_1 &= \sqrt[3]{\frac{\sigma_T A \mu_f}{\rho_f^2}}, \\
C_2 &= \sqrt[3]{\frac{\sigma_T A \rho_f}{\mu_f^2}}, \\
A &= \frac{\Delta T}{x^{n+1}} 5, \\
B &= \frac{\Delta C}{x^{n+1}} 5.
\end{aligned} \tag{3}$$

The dimensionless system is defined by

$$\frac{1}{\phi_1} f''' [\eta] + \frac{2+n}{3} f [\eta] f'' [\eta] - \frac{2n+1}{3} f'^2 [\eta] - \phi_2 M f' [\eta] = 0, \tag{4}$$

$$\begin{aligned}
\phi_3 (1 + R d) \theta'' [\eta] + \frac{2+n}{3} Pr f [\eta] \theta' [\eta] \\
- (1+n) Pr f' [\eta] \theta [\eta] + Q \theta [\eta] = 0,
\end{aligned} \tag{5}$$

$$g'' [\eta] + \frac{2+n}{3} Sc f [\eta] g' [\eta] - (1+n) Sc f' [\eta] g [\eta] = 0, \tag{6}$$

$$\begin{aligned}
f(0) &= 0, \\
f'(0) &= 1, \\
\theta(0) &= 1, \\
g(0) &= 1, \\
f'(\infty) &\longrightarrow 0, \\
\theta(\infty) &\longrightarrow 0, \\
g(\infty) &\longrightarrow 0.
\end{aligned} \tag{7}$$

The flow-controlling parameters and constant terms appearing in expressions (4–7) are listed as follows: magnetic parameter ($M = \sigma_f B_0^2 / C_1 C_2 \rho_f$); Prandtl number ($Pr = \nu_f / \alpha_f$); Schmidt number ($Sc = \alpha / D_m$); heat generation parameter ($Q = Q_0 / (\rho c_p)_{nf}$); thermal radiation parameter ($R d = 16 \sigma^* T_\infty^3 / 3 k^* k_f$). Also,

$$\begin{aligned}
\phi_1 &= (1 - \phi)^{2.5} \left(1 - \phi + \phi \left(\frac{\rho_s}{\rho_f} \right) \right), \\
\phi_2 &= \frac{\sigma_{nf}}{\sigma_f} = 1 + \frac{3\phi((\sigma_s/\sigma_f) - 1)}{((\sigma_s/\sigma_f) + 2) - \phi((\sigma_s/\sigma_f) - 1)}, \\
\phi_3 &= \frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + 2\phi(k_f - k_s)}.
\end{aligned} \tag{8}$$

The mathematical form of Nusselt number is

$$Nu_x = \frac{x q_w|_{y=0}}{k_f (T_w - T_0)}, \tag{9}$$

where

$$q_w = (-k_{nf} \partial_y T + q_r). \tag{10}$$

The dimensionless Nusselt number is addressed by

$$Nu_x Re_x^{-0.5} = \frac{k_{nf}}{k_f} (1 + R d) \theta' (0), \tag{11}$$

in which $Re_x (= U_w x / \nu_f)$ describes the local Reynolds number.

3. Numerical Method and Validation

In this segment, governing coupled ODEs (4–6) with suitable boundary conditions (7) have been solved numerically by utilizing the Runge–Kutta–Fehlberg method with the help of computational software MATHEMATICA. In the current work, the steady 2-D ethylene glycol-water-based nanoliquid transport with magnetohydrodynamic effect is considered. The results of the current analysis are accurate and more useful in engineering problems. The following procedure is used to reduce the higher-order equations:

$$f = q_1,$$

$$f' = q_2,$$

$$f'' = q_3,$$

$$f''' = q'_3,$$

$$\theta = q_4,$$

$$\theta' = q_5,$$

$$\theta'' = q'_5,$$

$$g = q_6,$$

$$g' = q_7,$$

$$g'' = q'_7,$$

TABLE 1: Comparative study of $-\theta'(0)$ for varying Pr when $M = Q = R = d = \phi = 0$.

Pr	Ghalambaz et al. [49]	Khan and Pop [50]	Gorla and Sidawi [51]	Current results
0.7	0.4541	0.4539	0.4539	0.4540
2.0	0.9114	0.9113	0.9114	0.9115
7.0	1.8954	1.8954	1.8954	1.8954

FIGURE 2: Fluctuations of the velocity field $f'[\eta]$ against the (a) exponential constant n , (b) nanoparticle volume fraction ϕ , and (c) magnetic parameter M .

FIGURE 3: Fluctuations of the thermal field $\theta[\eta]$ against the (a) Prandtl number Pr , (b) nanoparticle volume fraction ϕ , (c) heat generation parameter Q , (d) exponential constant n , (e) thermal radiation parameter Rd , and (f) magnetic parameter M .

FIGURE 4: Fluctuations of the concentration field $g[\eta]$ against the (a) exponential constant n and (b) Schmidt number Sc .

$$\begin{aligned}
 q_3' &= \phi_1 \left(-(2 + n/3)q_1q_3 + (2n + 1/3)q_2^2 + \phi_2 M q_2 \right), \\
 q_5' &= \frac{-(2 + n/3)Prq_1q_5 + (1 + n)Prq_1q_4 - Qq_4}{\phi_3(1 + R d)}, \\
 q_7' &= \frac{2 + n}{3} Scq_1q_7 + (1 + n)Scq_2q_6, \\
 q_1(0) &= 0, \\
 q_2(0) &= 1, \\
 q_4(0) &= 1, \\
 q_6(0) &= 1, \\
 q_2(\infty) &\longrightarrow 0, \\
 q_4(\infty) &\longrightarrow 0, \\
 q_6(\infty) &\longrightarrow 0.
 \end{aligned} \tag{12}$$

In Table 1, the comparative study of $-\theta'(0)$ for different values of Pr with already published works in a limiting situation is presented. Here, we have seen good agreement between the currents results and already published works in this limiting situation. We have set the relative tolerance to 10^{-5} and acquired high-precision results for this scrutinization.

4. Results and Discussion

Figure 2(a) discloses the nature of the velocity field $f'[\eta]$ against an exponential constant n for the Ag-ethylene glycol/water nanofluid. It is noted that flow is exaggerated by increasing the estimations of the exponential constant n . Figure 2(b) is drawn to depict the behavior of the nanoparticle volume fraction ϕ versus the velocity profile $f'[\eta]$. It is depicted that the velocity field $f'[\eta]$ is a decreasing function of the nanoparticle volume fraction ϕ . Figure 2(c) displays the effect of M on velocity $f'[\eta]$ for the Ag-ethylene glycol/water nanofluid. It is analyzed that $f'[\eta]$ declines with larger M . When the magnetic parameter rises, a

significant resistance is created among the particles, causing heat to be developed in the fluid. A drag force termed “Lorentz force” was created by slapping the magnetic field. Figure 3(a) displays the estimations of the thermal field $\theta[\eta]$ via distinguished values of the Prandtl number Pr . It can be revealed that $\theta[\eta]$ declines with larger Pr . The Prandtl number has an inverse relationship with thermal diffusivity. As the Prandtl number rises, thermal diffusion weakens and the temperature distribution dissipates. The effects of nanoparticle volume fraction ϕ on the thermal field $\theta[\eta]$ are revealed through Figure 3(b). The increment in the thermal field $\theta[\eta]$ is observed by increasing values of the nanoparticle volume fraction ϕ . Figure 3(c) is designed to scrutinize the effect of the heat generation/absorption parameter Q on the thermal field $\theta[\eta]$. The thermal field $\theta[\eta]$ is boosted up with a larger heat generation/absorption parameter Q . Figure 3(d) is drawn to examine the variations of the thermal field $\theta[\eta]$ via the larger exponential constant n . From the variations of data, we observed that the thermal field $\theta[\eta]$ declines with greater magnitudes of exponential constant n . The consequence of $R d$ via the thermal field $\theta[\eta]$ is shown in Figure 3(e). Here, $\theta[\eta]$ is enhanced with increasing estimations of $R d$. For the higher thermal radiation parameter, the system’s interior energy source grows physically. As a result, the thermal profile rises. Figure 3(f) is depicted to visualize the impact of M on the thermal field $\theta[\eta]$. Here, the thermal field $\theta[\eta]$ is upgraded with an increase in magnetic parameter M . Physically, the magnetic field increases the temperature, resulting in a thickening of the thermal layer. It is apparent that temperature distribution has been improved. Figure 4(a) signifies the effect of exponential constant n against concentration field $g[\eta]$. It is analyzed that concentration $g[\eta]$ is reduced for larger estimations of the exponential constant n . Figure 4(b) is captured to observe the effect of Schmidt number Sc against concentration distribution $g[\eta]$. It is interesting to notice that concentration $g[\eta]$ is reduced via a larger Schmidt number Sc . Tables 2 and 3 display thermophysical features of nano-materials and base liquids.

TABLE 2: Thermophysical properties of nanomaterials [46].

Characteristics	Nanomaterials
Density	$\rho_{nf} = \rho_f (1 - \phi + \phi \rho_s / \rho_f)$
Viscosity	$\mu_{nf} = \mu_f / (1 - \phi)^{2.5}$
Thermal conductivity	$k_{nf}/k_f = k_s + 2k_f - 2\phi(k_f - k_s)/k_s + 2k_f + 2\phi(k_f - k_s)$
Heat capacity	$(\rho c_p)_{nf} = (\rho c_p)_f (1 - \phi + \phi(\rho c_p)_s / (\rho c_p)_f)$
Electric conductivity	$\sigma_{nf}/\sigma_f = 1 + 3(\sigma - 1)\phi/(\sigma + 2) - (\sigma - 1)\phi$

TABLE 3: Thermophysical properties of the base liquid and nanomaterials [46].

Properties	MoS ₂	Ethylene glycol-water (50–50%)
ρ (kg/m ³)	5060	1063.8
k (W/mK)	904.4	400
c_p (J/kgK)	397.21	385
σ (Ω.m)	2.09×10^{-4}	9.75×10^{-4}

5. Conclusions

In this work, incompressible two-dimensional ethylene glycol- (50 – 50%) water-based nanoliquids containing molybdenum disulfide (MoS₂) particles over a stretching surface has been scrutinized. The analysis is executed during occurrences of thermal radiation and heat absorption/generation. Similarity transformations are used on the system of PDEs to get nondimensional ODEs. The obtained nondimensional ODEs are solved with the help of the Runge–Kutta–Fehlberg method via computational software MATHEMATICA. With increasing estimations of the exponential constant, the velocity field of the nanofluid enhances. The Prandtl number and nanoparticle volume fraction have opposite impacts on the thermal field [52–54]. The larger values of the thermal radiation parameter lead to a stronger thermal field. The concentration distribution is reduced with a higher exponential constant.

Nomenclature

u, v : Velocity components (ms^{−1})
 C_0 : Ambient concentration (mol.L^{−1})
 x, y : Coordinates system (m)
 T_w : Surface temperature (K)
 B_0 : Magnetic field strength (Nm^{−1}A^{−1})
 C_w : Surface concentration (mol.L^{−1})
 T : Temperature (K)
 M : Magnetic parameter
 q_r : Radiative heat flux
 Rd : Thermal radiation parameter
 Q_0 : Coefficient of heat generation/absorption
 g : Dimensionless concentration
 C : Concentration (mol.L^{−1})
 Q : Heat generation/absorption parameter
 T_0 : Ambient temperature (K)
 Sc : Schmidt number
 n : Exponent constant
 Pr : Prandtl number

Greek symbols and subscripts

μ_{nf} : Dynamic viscosity of the nanofluid (Pas)
 w : Wall condition
 σ_{nf} : Electric conductivity (Ω^{−1}m^{−1})
 nf : Nanofluid
 ρ_{nf} : Density of the nanofluid (kgm^{−3})
 f : Base fluid
 k_{nf} : Thermal conductivity of the nanofluid (Wm^{−1}K^{−1})
 s : Solid particle
 $(\rho c_p)_{nf}$: Specific heat (J.Kg^{−3}.K^{−1})
 $(\rho c_p)_f$: Base fluid specific heat (J.Kg^{−1}.K^{−1})
 ϕ : Volume fraction of the nanoparticle
 θ : Dimensionless temperature.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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