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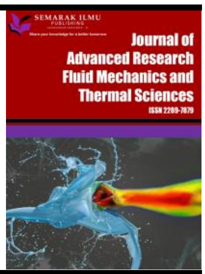

The Mixed of Hybrid Nanofluid GO-MoS_2/Engine Oil Over a Shrinking Sheet with Mass Flux Effect: Reiner-Philippoff Model

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ABSTRACT

The mixed convection flow and heat transfer of the hybrid nanofluid over a shrinking sheet are investigated. Molybdenum disulphide (MoS_2) and graphene oxide (GO) are employed as two hybrid nanoparticles while engine oil (EO) as the base fluid is considered. In this study, the Reiner-Philippoff model as one of non-Newtonian types is deliberated since it has the ability to function on three distinct types of fluids: viscous, shear thickening and shear thinning. The Reiner-Philippoff relation, the momentum and energy equations under Tiwari and Das model are all employed in the study. Influences from mass flux are also considered in the flow. Before computation using the bvp4c function in MATLAB, the respected equations are first converted into ordinary differential equation form using the similarity transformation. When the established and current models are discovered to be identical in a specific case, a direct comparative investigation is conducted to confirm the correctness of the current model. In addition, the present results are shown graphically and in tabular form. It is hypothesized that the presence of a hybrid nanofluid significantly affects the fluid characteristic and gives more satisfactory results than a single nanofluid. The skin friction coefficient and heat transfer rate of hybrid nanofluids are greater than the nanofluids. In terms of velocity and temperature profile, the reduction in velocity and the enhancement in temperature profile are caused by a rise in the Reiner-Philippoff parameter. The same outcome is also seen when the volume fraction of hybrid nanofluids increases.

1. Introduction

An efficient working fluid is required for industrial and technological applications to regulate processes and produce superior final products. Although many processes use non-Newtonian types of fluid to accelerate advancements, pure water (Newtonian) is still used as a cooling agent in many of them. There are numerous non-Newtonian fluid varieties that each have unique characteristics. In

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contrast to the Newtonian type of fluid, whose strain is in line with the stress tensor, the non-Newtonian type of fluid is classified by either shear-thickening or shear-thinning. Shear-thinning fluid shows the behavior of Newtonian fluids at extreme shear rates, whereas shear-thickening fluids show the development in viscosity proportional to shear rate. As indicated in Deshpande *et al.*, [1] the models that represent shear-thickening and shear-thinning characteristics include the Powell-Eyring, Sisko, Carreau-Yasuda, Carreau viscosity, and as well as Reiner-Philippoff models. The Reiner-Philippoff model, which belongs to the non-Newtonian group, is the most fascinating to study because it exhibits Newtonian fluid behavior at low or high values of shear stress and non-Newtonian behavior at other values. Many researchers paid attention to the Reiner-Philippoff model investigation because of its enormous significance in engineering applications [2-10]. Furthermore, the Reiner-Philippoff model is essential and unique in representing natural fluid in industrial applications. In certain situations, it can exhibit three fluid characteristics where it can behave like Newtonian, dilatant, and pseudo-plastics. This is significant in manufacturing procedures since the applied fluid might vary in a specific process to achieve the best production. In addition, numerous research examined the flow's movement over various geometries and its effects on the flow field [11-23].

The process by which heat is transferred from one medium to another by the movement of fluids is known as convection. There are two types of convection: 1) forced convection - the process by which fluid motion is generated from an external source, and 2) natural or free convection - the phenomenon in which buoyant forces which result from changes in density are the only source of fluid motion. When forced and natural convection systems merge, mixed convection is formed. Due to the significance of mixed convection flow in industrial systems including nuclear reactors, solar collectors, heat exchangers, and electronic devices, academics are particularly fascinated with the topic. For instance, Merkin [24] investigated the mixed convection flow towards a vertical plate in a porous substance. He discovered that dual solutions are possible for particular values of the mixed convection parameter, for which Merkin [25] had previously shown that these solutions were stable. Ingham [26] also discovered the mixed convection flow over a moving vertical flat plate. Ramachandran *et al.,* [27] then applied this work to the stagnation flow problem and discovered that the opposing flow area was where the solution's non-uniqueness occurred. Similar behavior was seen in the mixed convection stagnation flow of a micropolar fluid by Lok *et al.,* [28]. Dual solutions for the assisting flow concurrently with the opposing flow were also discovered by Ishak *et al.,* [29]. In addition, Harris *et al.,* [30], Zokri *et al.,* [31], Khashi'ie *et al.,* [32,33], Ghalambaz *et al.,* [34], Waini *et al.,* [35,36], have also considered the work on the mixed convection flow.

In recent years, hybrid nanofluids have taken the place of nanofluids in several technologies to enhance thermal performance. In their experimental work, Turcu *et al.,* [37] and Jana *et al.,* [38] appear to be among the first researchers to integrate hybrid nano-composite particles into consideration. A hybrid nanofluid is an innovative fluid that contains several nanoparticles and can increase the rate of heat transfer due to its synergistic effects [39]. Additionally, the appropriate nanoparticles can be combined or hybridized to achieve the optimum heat transfer [40]. A fundamental requirement of the modern world is the rate of heat transfer. Many scientists and researchers are working on methods for expediting heat transfer rates. Engine oil is one of the base fluids that many researchers have recently employed. It is treated as blood for automobiles, plays a crucial part in how the machine functions, and is most vitally used to lubricate and clean the engine [41]. Asadi *et al.,* [42] examined thermophysical properties and heat transmission performance using MWCNT + ZnO in engine oil hybrid nanofluid. In their experimental study using WO_3+MWCNTs in regular engine oil, Aghahadi *et al.,* [43] conducted research on the rheological behavior of a hybrid nanofluid, while Soltani *et al.,* [44] discovered that the engine oil's thermal conductivity increased by up to 19.85%. Omrani *et al.,* [45] recently investigated the impact of adding some micro- and nanosized particles to engine oil to speed up heat transfer. Huang *et al.,* [46] discussed how graphene oil nanofluid performs tribologically in rotation phenomena. While Arif *et al.,* [47] studied engine oil as a base fluid and considered using nanoparticles to expedite heat transfer. They discussed some crucial applications of engines that make use of nanoparticles in base fluid engine oil. Additionally, in another research, Arif *et al.,* [48] employed engine oil as the base fluid and GO+MoS_2 as the Maxwell hybrid nanofluid (MHNF). They discovered that MHNF speeds up heat transport by up to 23.17%.

The character of the flow across a stretching and shrinking surface in a hybrid nanofluid with temporal stability analysis was described by Waini *et al.,* [49]. They discovered that one of the solutions was shown to be unstable over time. The problem of a hybrid nanofluid flow over a stretching/shrinking sheet was then extended to encompass a variety of facets, as discussed by Waini *et al.,* [50-52]. The boundary layer flow of a hybrid nanofluid has also been addressed in several articles, with the influence of different physical parameters past a stretching and shrinking sheet/surface [53-58].

In the present study, the nanoparticles of graphene oxide (GO) and molybdenum disulfide (MoS_2) were considered with engine oil (EO) as a base fluid. GO is a unique material that can be viewed as a single monomolecular layer of graphite with various oxygen-containing functionalities such as epoxide, carbonyl, carboxyl, and hydroxyl groups. The membranes with GO incorporation show excellent mechanical and thermal stability. As a result, GO has seen significant use in various sectors, including catalysis, energy storage, biomedical applications, nanocomposite materials, polymer composite materials, and as a surfactant. Molybdenum disulfide (MoS_2), also known as moly, is an inorganic metallic compound composed of molybdenum and sulfur. This substance has a crystal lattice-layered structure, and it occurs in natural conditions as the mineral molybdenite (the principal ore of molybdenum). It has numerous industrial and commercial applications, including lubricants and is also the perfect material for low-friction materials because of its low reactivity. This substance's low coefficient of friction and chemical inertness are why it is regarded as a helpful lubricant. Engine oil (EO) represents crucial importance in the automotive sector. To maintain performance and improve the thermal mechanism of engine oil base fluid with applications of hybrid-nanofluid, engine oil thermal capacitance is required. The employment of graphene oxide and molybdenum disulfide nanoparticles supports the thermal mechanism of a hybrid nanofluid in EO. Applications in the auto sector are the driving forces behind the idea of suspending engine oil with graphene oxide and molybdenum nanoparticles.

Motivated by the above literature survey, this study focuses on the mixed convection of Reiner-Philippoff hybrid nanofluid, which was inspired by a study in the literature that used the unique Reiner-Philippoff fluid model. The flow is expected to pass across a shrinking sheet. Also, as engine oil is regarded as a base fluid, GO-MoS_2 nanoparticles are embedded to the engine oil to expedite the heat transfer rate. Influences from mass flux are also considered in the flow. The respected equations are first converted into ordinary differential equation form using the similarity transformation before it solves computationally using the bvp4c function in MATLAB. The findings are presented graphically along with a brief discussion of how various physical factors were influenced. To the best knowledge, this problem has not been studied before, so the reported results are new. It is vital to mention that the proposed model sheds light on the complex fluid that predominates in practical applications. Additionally, the proposed model which is examined along with the implication of mixed convection, provides a clearer understanding of what transpired in technologically advanced applications. Another intriguing feature of this model is that in certain circumstances, it can be used to simulate Newtonian fluid where the model's validity may be verified using established output from the literature. Furthermore, since the Reiner-Philippoff fluid can resemble the shear-thinning fluid which exhibits pseudoplastic behavior, it is frequently used in oil and gas drilling, roller-bearing operations, mixing vessels mostly in food industries, dampers or hydrodynamics bearing, polymer processing, and catalytic chemical reactors. Meanwhile, the shear-thickening fluid which exhibits dilatant behavior is used in many commercial applications like the fabrication of protective gear or equipment such as body armor, vests, army gear and sporting protective clothing as well as other types of materials used for protection.

2. Methodology

Figure 1 depicts the physical configuration of Reiner-Philippoff nanofluid across a shrinking surface where the velocity's surface is $u = ax^{1/3}f'(\eta)$ with $a > 0$. The mass flux velocity $v_w(x)$ represents the surface permeability, while given $T_w = T_\infty + T_0 x^{-1/3}$ is the surface temperature where the constant ambient temperature is T_∞ and T_0 is the reference temperature. Additionally, both the fluid and surface were at rest and in steady state with the ambient temperature. Thus, the comprehensive equations for the suggested model are as follows [5,6]:

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

$$\frac{\partial u}{\partial y} = \frac{\tau}{\mu_\infty + \dfrac{\mu_{hnf} - \mu_\infty}{1 + \left(\dfrac{\tau}{\tau_s}\right)^2}} \tag{2}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{hnf}}\frac{\partial \tau}{\partial y} + \frac{(\rho\beta)_{hnf}}{\rho_{hnf}} g^*\left(T - T_\infty\right) \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{hnf}}{\left(\rho C_p\right)_{hnf}}\frac{\partial^2 T}{\partial^2 y} \tag{4}$$

subject to:

$$\begin{aligned} &u = \varepsilon u_w(x),\ v = v_w(x),\ T = T_w \ \text{ at } \ y = 0 \\ &u \to 0,\ T \to T_\infty \ \text{ as } \ y \to \infty \end{aligned} \tag{5}$$

where (u, v) are the velocity components in the (x, y) directions, respectively. Further, ρ_{hnf} is fluid density, $(\rho\beta)_{hnf}$ is thermal expansion, $\left(\rho C_p\right)_{hnf}$ is heat capacity, k_{hnf} is thermal conductivity, μ_{hnf} is dynamic viscosity, μ_∞ is limiting dynamic viscosity, T is temperature, g is acceleration due to gravity, τ is shear stress of Reiner-Philippoff fluid, τ_s is references shear stress and ε is stretching/shrinking parameter. The subscripts of *hnf* and *f* stand for hybrid nanofluid and fluid, respectively.

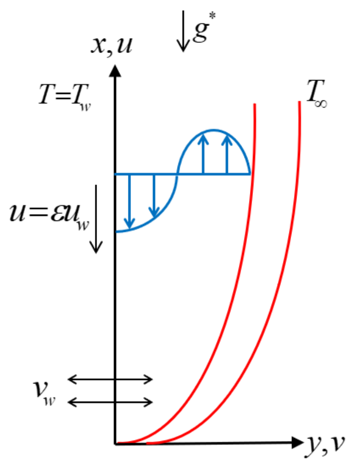

Fig. 1. The physical model

Employing similarity transformation as [59]:

$$\psi = \sqrt{a\nu_f}\, x^{2/3} f(\eta),\ \tau = \rho_f \sqrt{a^3 \nu_f}\, g(\eta),\ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty},\ \eta = \frac{y}{x^{1/3}}\sqrt{\frac{a}{\nu_f}} \tag{6}$$

The term ψ is express by $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$ yield:

$$u = a x^{1/3} f'(\eta),\ v = -\sqrt{a\nu_f}\, x^{-1/3}\left(\frac{2}{3} f(\eta) - \frac{1}{3}\eta f'(\eta)\right) \tag{7}$$

At $\eta = 0$, the wall mass flux velocity obtained as:

$$v_w(x) = -\frac{2}{3}\sqrt{a\nu_{hnf}}\, x^{-1/3} S \tag{8}$$

in which $f(0) = S$ indicate the parameter of constant mass flux. There are three different situations of the value of S, where S = 0 denote the impermeable surface, S < 0 for injection and S > 0 is for suction, while $\nu_f = \mu_\infty/\rho_f$ is the fluid kinematic viscosity. The similarity Eq. (9) to Eq. (12) are obtained after employing Eq. (6) and Eq. (7):

$$g = f''\left(\frac{g^2 + \left(\frac{\mu_{hnf}}{\mu_f}\right)\lambda\gamma^2}{g^2 + \gamma^2}\right) \tag{9}$$

$$g' - \frac{\rho_{hnf}}{\rho_f}\left(\frac{1}{3} f'^2 - \frac{2}{3} f f''\right) + \left[\frac{(\rho\beta)_{hnf}}{(\rho\beta)_f}\right] Z\theta = 0 \tag{10}$$

$$\frac{1}{\Pr}\left[\frac{k_{hnf}}{k_f}\right]\theta'' + \left[\frac{\left(\rho C_p\right)_{hnf}}{\left(\rho C_p\right)_f}\right]\left(\frac{1}{3}f'\theta + \frac{2}{3}f\theta'\right) = 0 \tag{11}$$

subject to:

$$\begin{aligned} &f(0) = S,\ f'(0) = \varepsilon,\ \theta(0) = 1 \\ &f'(\eta) \to 0,\ \ \theta(\eta) \to 0 \ \text{ as } \ \eta \to \infty \end{aligned} \tag{12}$$

The dimensionless parameter Bingham number γ, Reiner–Philippoff fluid λ, mixed convection Z, and Prandtl number Pr, are defined by:

$$\gamma = \frac{\tau_s}{\rho_f \sqrt{a^3 \nu_f}},\ \lambda = \frac{\mu_f}{\mu_\infty},\ Z = \frac{Gr_x}{\mathrm{Re}_x^2} = \frac{g^*(\beta)_f T_0}{a^2},\ \Pr = \frac{(\mu C_p)_f}{k_f} \tag{13}$$

Note that, $\lambda = 1$ presenting viscous Newtonian type, whereas $\lambda > 1$ signify the shear-thinning and $\lambda < 1$ is shear thickening fluid type respectively. Further, $\varepsilon = 0$ signifies the static sheet, $\varepsilon > 0$ indicate the stretching sheet and $\varepsilon < 0$ is the shrinking sheet. The quantity of physical in term of skin friction and local Nusselt number are given by:

$$C_f = \frac{\tau_w}{\rho_f u_w^2},\ Nu_x = \frac{x q_w}{k_f\left(T_w - T_\infty\right)} \tag{14}$$

where:

$$\tau_w = \rho_f \sqrt{a^3 \nu_f}\left(g(\eta)\right)_{y=0},\ \ q_w = -k_{hnf}\left.\left(\frac{\partial T}{\partial y}\right)\right|_{y=0} \tag{15}$$

The τ_w symbolizes the quantity of τ on $y = 0$, and q_w presenting the surface heat flux. Then, one gets:

$$\mathrm{Re}_x^{1/2} C_f = g(0),\ \mathrm{Re}_x^{-1/2} Nu_x = -\frac{k_{hnf}}{k_f}\theta'(0) \tag{16}$$

where $Re_x = u_w(x)x/\nu_f$ is the local Reynolds number and $Gr_x = \left(g^*(\beta_T)_f\left(T_0 x^{-1/3}\right)x^3\right)/\nu_f^2$ is the Grashof number.

The physical properties of GO, MoS_2, and EO are listed in Table 1, whereas the thermophysical characteristics of nanofluid and hybrid nanofluid are listed in Table 2.

Table 1
Thermophysical properties of engine oil and nanoparticles [47,48,60]

Thermophysical properties	EO	GO	MoS_2
ρ (kg/m^3)	884	1800	5060
C_p (J/kgK)	1910	717	397.21
K (W/mK)	0.144	5000	904.4
B$x10^{-5}$ (1 / K)	70	0.284	2.8424

Table 2
Mathematical expression for the thermophysical properties of *hnf* [48,61]

Thermophysical properties	Hybrid nanofluid
Density	$\rho_{hnf} = \left(1-\phi_{hnf}\right)\rho_f + \phi_{GO}\rho_{GO} + \phi_{MoS_2}\rho_{MoS_2}$
Heat capacity	$\left(\rho C_p\right)_{hnf} = \left(\rho C_p\right)_f \left(1-\phi_{hnf}\right) + \phi_{GO}\left(\rho C_p\right)_{GO} + \phi_{MoS_2}\left(\rho C_p\right)_{MoS_2}$
Dynamic viscosity	$\mu_{hnf} = \dfrac{\mu_f}{\left(1-\left(\phi_{GO}+\phi_{MoS_2}\right)\right)^{2.5}}$
Thermal conductivity	$\dfrac{k_{hnf}}{k_f} = \dfrac{2k_f + \dfrac{\left(\phi_{GO}k_{GO}+\phi_{MoS_2}k_{MoS_2}\right)}{\phi_{hnf}} + 2\left(\phi_{GO}k_{GO}+\phi_{MoS_2}k_{MoS_2}\right) - 2k_f\phi_{hnf}}{2k_f + \dfrac{\left(\phi_{GO}k_{GO}+\phi_{MoS_2}k_{MoS_2}\right)}{\phi_{hnf}} + \left(\phi_{GO}k_{GO}+\phi_{MoS_2}k_{MoS_2}\right) - k_f\phi_{hnf}}$
Thermal expansion	$\left(\rho\beta_T\right)_{hnf} = \left(\rho\beta_T\right)_f \left(1-\phi_{hnf}\right) + \phi_{GO}\left(\rho\beta_T\right)_{GO} + \phi_{MoS_2}\left(\rho\beta_T\right)_{MoS_2}$
	where $\phi_{hnf} = \phi_{GO} + \phi_{MoS_2}$

3. Results and Discussion

The numerical solutions of Eq. (9) to Eq. (12) are obtained using the boundary value problem solver, bvp4c, a feature of the MATLAB software. It uses the three-stage Lobatta IIIa formula and is a finite difference approach. The choice of the initial guess and the thickness of the boundary layer η_∞, will rely on the parameters utilised to obtain the required solutions. This solver is also being utilized by various researchers to solve boundary layer flow problems [62,63].

A direct comparison analysis is conducted on the existing value of $f''(0)$ provided by Cortell [64], Ferdows *et al.,* [65], and Waini *et al.,* [18] to vouch for the dependability of the current model. It should be noted that the equations on the current model were the same for the limiting case, making a comparison between the present findings and the current output appropriate. In Table 3 and Table 4, respectively, the validation data on the values of $f''(0)$ are presented. The comparison reveals excellent agreement, which supports the current mathematical formulation and the provided numerical results.

To strengthen the current formulation and the current result, the values of $g(0)$ are also compared with the output reported by Reddy *et al.,* [10] and Waini *et al.,* [66] for various values of the Reiner-Philippoff fluid parameter λ, the Bingham number γ, and the Prandtl number, Pr = 2. Strong agreement can be seen in the comparison; hence Table 5 and Table 6 show the corresponding numerical values. For higher values of γ, the values of $g(0)$ significantly increase. With the rise of λ, there is, however, a slight decrease in the values of $g(0)$.

Table 3
Comparative model in terms of momentum equations

Author	Model (momentum)	Limiting cases
Current	$g' - \frac{\rho_{hnf}}{\rho_f}\left(\frac{1}{3}f'^2 - \frac{2}{3}ff''\right) + \left[\frac{(\rho\beta)_{hnf}}{(\rho\beta)_f}\right]Z\theta = 0$	*Z* = 0
Cortell [64]	$3f''' + 2ff'' - (f')^2 = 0$	-
Ferdows *et al.,* [65]	$f''' + \frac{2}{3}ff'' - \frac{1}{3}\left(f'^2 + Mf'^2\right) + Gr\theta + Gc\phi = 0$	*M* = *Gr* = *Gc* = 0
Waini *et al.,* [18]	$3\frac{\mu_{hnf}/\mu_f}{\rho_{hnf}/\rho_f}f''' + 2ff'' - f'^2 = 0$	-

Table 4
Comparative value of $f''(0)$ at $\varepsilon = \lambda = \gamma = 1$, Pr = 2 and *Z* = 0 for different value of *S*

S	Cortell [64]	Ferdows *et al.,* [65]	Waini *et al.,* [18]	Current
-0.75	-0.453521	-0.453523	-0.453523	-0.453523325
-0.5	-0.518869	-0.518869	-0.518869	-0.518869429
0	-0.677647	-0.677648	-0.677648	-0.677647983
0.5	-0.873627	-0.873643	-0.873643	-0.873642863
0.75	-0.984417	-0.984439	-0.984439	-0.984439388

Table 5
Comparative model in terms of momentum equations

Author	Model (momentum)	Limiting cases
Current	$g' - \frac{\rho_{hnf}}{\rho_f}\left(\frac{1}{3}f'^2 - \frac{2}{3}ff''\right) + \left[\frac{(\rho\beta)_{hnf}}{(\rho\beta)_f}\right]Z\theta = 0$	*Z* = 0
Sajid *et al.,* [10]	$g' + \frac{2}{3}ff'' - \frac{1}{3}f'^2 = 0$	-
Waini *et al.,* [66]	$g' + \frac{2}{3}ff'' - \frac{1}{3}f'^2 - M\sin^2(\beta)f' = 0$	*M* = 0

Table 6
Comparative value of *g*(0) for *λ* and *γ* when *S* = *Z* = 0 and $\varepsilon = 1$

γ	λ	Sajid *et al.,* [10]	Waini *et al.,* [66]	Current
0.1	0.1	-0.660273	-0.660275	-0.660275189
0.5		-0.380604	-0.380604	-0.380603983
1		-0.246415	-0.246415	-0.246414994
0.1	0.3	-0.664497	-0.664498	-0.664497827
	0.5	-0.668484	-0.668486	-0.668486422
	0.7	-0.672282	-0.672277	-0.672276682

Figure 2 and Figure 3 illustrate how *λ* and *γ* affect variations in $Re_x^{1/2}C_f$ and $Re_x^{-1/2}Nu_x$ when *ε* = 1, Pr = 21 and *S* = *Z* = 0. The increase in $Re_x^{-1/2}Nu_x$ (except at *γ* = 0.1) and the decrease in $Re_x^{1/2}C_f$ were both influenced by an increase in *λ*. When *γ* = 0.1, 0.3, 0.5 and *λ* = 1 (Newtonian fluid), the values of $Re_x^{1/2}C_f$ = -0.67764798 and $Re_x^{-1/2}Nu_x$ = 3.75348202 remain unchanged (see Table 7).

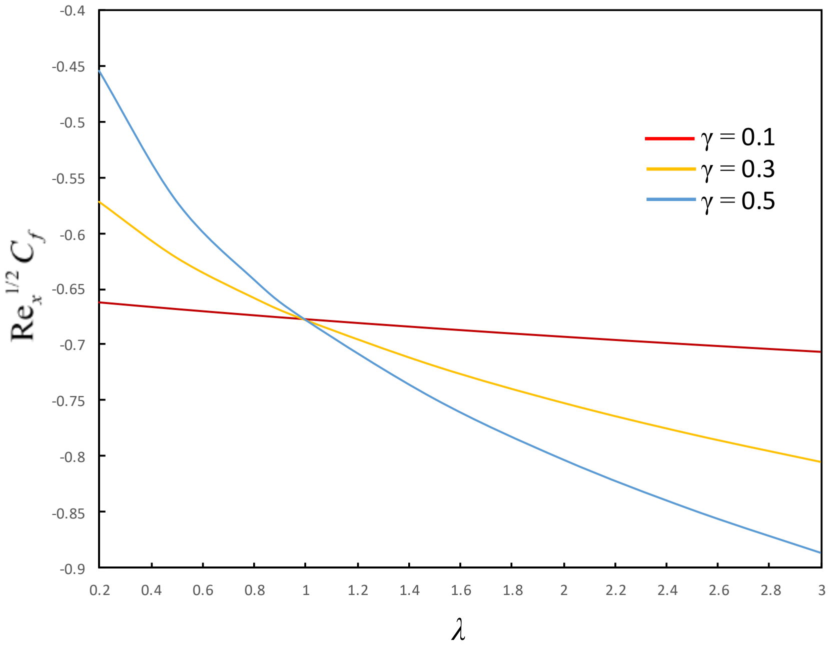

Fig. 2. $Re_x^{1/2}C_f$ vs λ for various values of γ

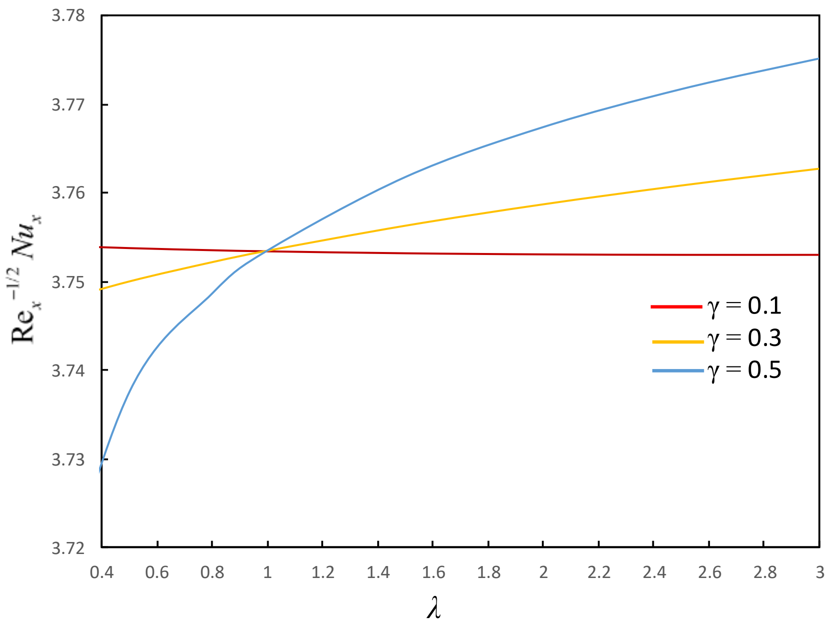

Fig. 3. $Re_x^{-1/2}Nu_x$ vs λ for various values of γ

Further, as γ increases, it becomes clear that the quantity of $Re_x^{1/2}C_f$ rises when $\lambda < 1$ (shear-thickening fluid) and decreases when $\lambda > 1$ (shear-thinning fluid), while the thermal rate yields opposite outcomes. Additionally, for future references, Table 7 tabulates the computed values of $Re_x^{1/2}C_f$ and $Re_x^{-1/2}Nu_x$ with various values of λ and γ.

This work has examined the thermal characteristics of the hybrid nanofluid and nanofluid to assess the thermal behaviour of a hybrid nanofluid (GO-MoS_2/EO) and a nanofluid (GO/EO and MoS_2/EO). The quantities of $Re_x^{1/2}C_f$ and $Re_x^{-1/2}Nu_x$ against Z for different values of fluids (regular engine oil, nanofluids and hybrid nanofluid) are tabulated in Table 8. The comparison of a (GO-MoS_2/EO) with (MoS_2/EO), (GO/EO) and regular EO are also plotted in Figure 4 and Figure 5. This study's primary goal is to assess the heat transfer rate of hybrid nanofluid in EO and evaluate the outcomes with a nanofluid. As can be seen from the comparison, the (GO-MoS_2/EO) has a higher rate of heat transfer than (MoS_2 + EO), (GO + EO), and regular EO. The (GO-MoS_2/EO) and (MoS_2 + EO) yield the greatest results for the rate of heat transfer. Physically, hybrid nanoparticles increased the thermal conductivity, which increased the rate of heat transfer in both nanofluids.

Table 7

Values of $Re_x^{1/2}C_f$ and $Re_x^{-1/2}Nu_x$ for λ and γ when ε = 1, Pr = 21 and $S = Z = 0$

λ	$Re_x^{1/2}C_f$			$Re_x^{-1/2}Nu_x$		
	γ = 0.1	γ = 0.3	γ = 0.5	γ = 0.1	γ = 0.3	γ = 0.5
0.5	-0.66848642	-0.62158953	-0.571307799	3.75383530	3.750043514	3.737631739
1.0	-0.677647983	-0.677647981	-0.677647983	3.75348202	3.753482015	3.753482015
1.5	-0.68591905	-0.718769932	-0.748419859	3.75326718	3.756288435	3.761767024

Table 8

Values of $Re_x^{1/2}C_f$ and $Re_x^{-1/2}Nu_x$ for selected values of regular engine oil, nanofluids, hybrid nanofluid and *Z* when ε = -1, Pr = 21, λ = 1.5, γ = 0.1 and *S* = 2.4

	$Re_x^{1/2}C_f$			
Z	*Regular EO*	*GO + EO*	*MoS_2 + EO*	*GO + MoS_2+EO*
-1	1.070639148	1.091231998	1.173068981	1.192058246
-0.5	1.086811156	1.107956731	1.189619042	1.208949090
0	1.102979760	1.124678016	1.206167067	1.225838040
0.5	1.119144981	1.141395883	1.222713059	1.242725103
1	1.135306870	1.158110367	1.239257033	1.259610293

	$Re_x^{-1/2}Nu_x$			
Z	*Regular EO*	*GO + EO*	*MoS_2 + EO*	*GO + MoS_2 + EO*
-1	32.97603626	32.87190642	33.01678707	33.36337800
-0.5	32.97620496	32.87209622	33.01697204	33.36344330
0	32.97637356	32.87228593	33.01715694	33.36350857
0.5	32.97654208	32.87247554	33.01734178	33.36357383
1	32.97671052	32.87266505	33.01752656	33.36363906

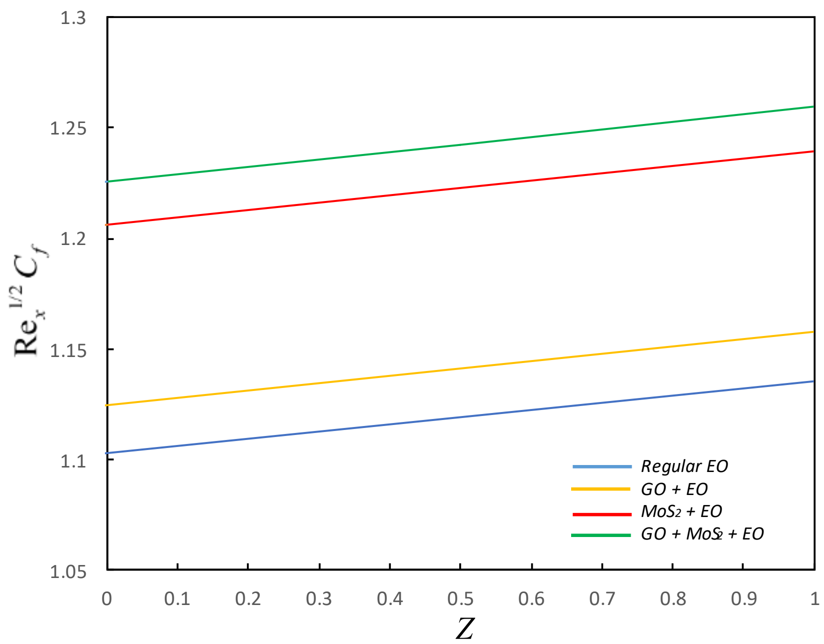

Fig. 4. $Re_x^{1/2} C_f$ vs *Z* for selected values of engine oil, nanofluids, and hybrid nanofluid

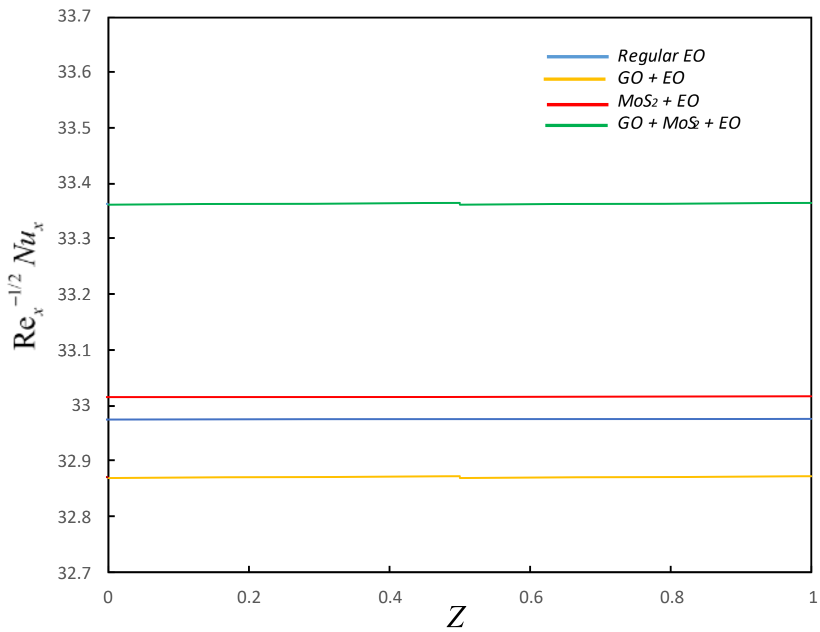

Fig. 5. $\mathrm{Re}_x^{-1/2} Nu_x$ vs *Z* for selected values of engine oil, nanofluids, and hybrid nanofluid

The quantities of $Re_x^{-1/2} Nu_x$ against Z for the different volume fractions of MoS_2 $\left(\phi_{MoS_2}\right)$ are tabulated in Table 9. Results show that the values of $Re_x^{-1/2} Nu_x$ increase with the rising of Z and the volume fraction, ϕ_{MoS_2} . The assisting flow ($Z > 0$) has a greater heat transfer than the opposing flow ($Z < 0$). A higher wall temperature than the fluid temperature indicates heat is transferred from the wall to the fluid in the assisting flow. Yet, the opposing flow has the opposite effect. Hence, the heat transfer process for an assisting flow is always greater than an opposing flow. This heat transmission rate is quite efficient and advantageous for the thermal performance of engine oil utilised in various machines.

Table 9
Values of $Re_x^{-1/2}Nu_x$ for selected values of ϕ_{MoS_2} and Z when ε = -1, Pr=21, λ = 1.5, γ = 0.1, S = 2.4 and ϕ_{GO} = 0.005

Z	$Re_x^{-1/2}Nu_x$		
	ϕ_{MoS_2} = 0.015	ϕ_{MoS_2} = 0.025	ϕ_{MoS_2} = 0.035
-1	32.964406627	33.023130232	33.061146140
-0.5	32.976900377	33.023359340	33.061400883
0	32.984620580	33.023588381	33.061655553
0.5	32.984826969	33.023817355	33.061910149
1	32.985033293	33.024046262	33.062164674

The velocity $f'(\eta)$ and temperature $\theta(\eta)$ profiles for selected parameters are provided in Figure 6 to Figure 13. These profiles asymptotically satisfy the boundary condition, thus supports the validity of the numerical results. The analysis of the temperature and velocity profiles employing Reiner-Philippoff parameters is shown in Figure 6 and Figure 7, respectively. The profiles demonstrate that the fluid's velocity decreases as λ increases, while temperature profiles exhibit the opposite behaviour. Figure 8 and Figure 9, and Figure 10 and Figure 11 showed the analysis of velocity and temperature profile with the variation of S and Z, respectively. The increasing behaviour is observed with the increasing of S and Z as portrayed in Figure 8 and Figure 10. However, the temperature profiles as displayed in Figure 9 and Figure 11 shows a contradictory behaviour. The volume fraction for the hybrid nanofluid GO-MoS_2/EO was highlighted in Figure 12. As in the figure, the velocity decreases as the volume fraction rises. It is a fact that increasing the values of the volume fractional parameter can cause resistance in the flow and slow down the fluid motion, which lowers the velocity of the hybrid nanofluid. While as shown in Figure 13, the temperature profile rises as the volume fraction of hybrid nanoparticles increase.

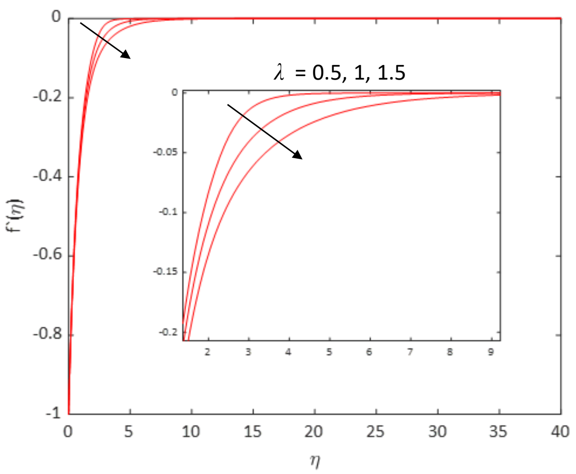

Fig. 6. $f'(\eta)$ for several values of λ and $\phi_{hnf} = 0.02$

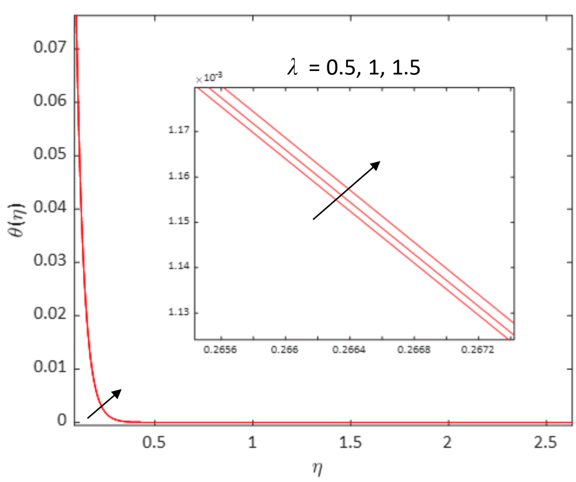

Fig. 7. $\theta(\eta)$ for several values of λ and $\phi_{hnf} = 0.02$

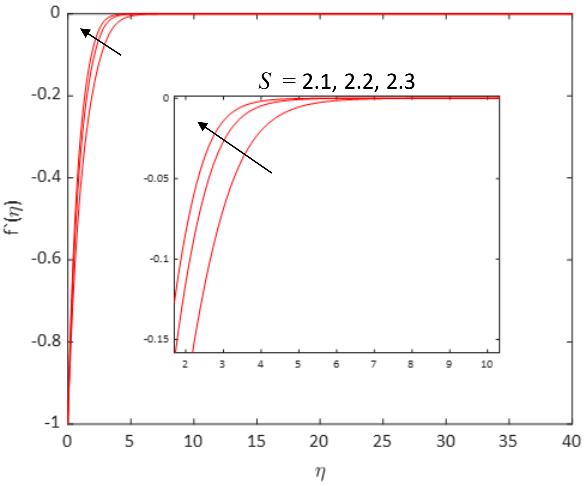

Fig. 8. $f'(\eta)$ for several values of S and $\phi_{hnf} = 0.02$

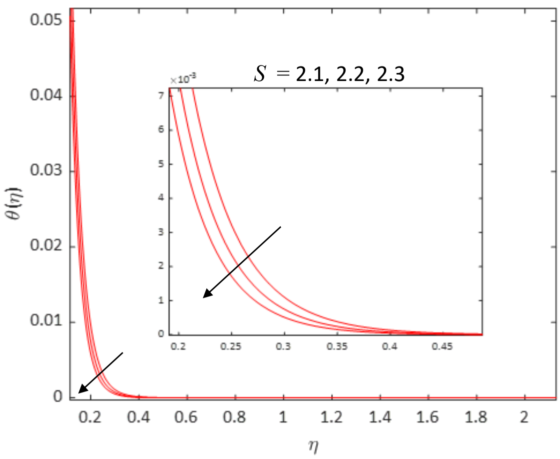

Fig. 9. $\theta(\eta)$ for several values of S and $\phi_{hnf} = 0.02$

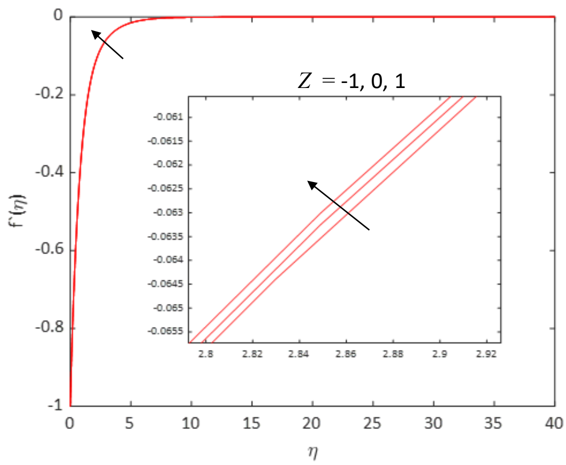

Fig. 10. $f'(\eta)$ for various values of Z and $\phi_{hnf} = 0.02$

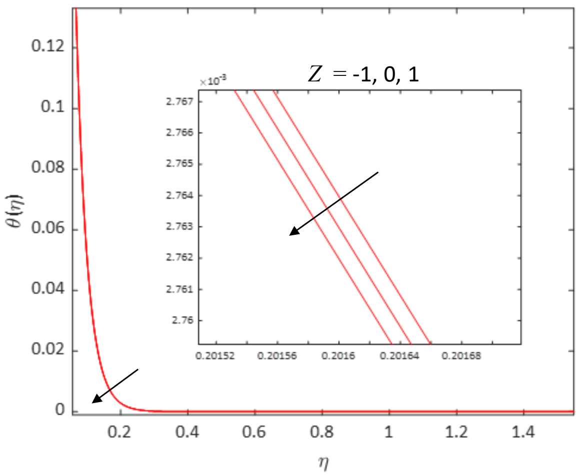

Fig. 11. $\theta(\eta)$ for various values of Z and $\phi_{hnf} = 0.02$

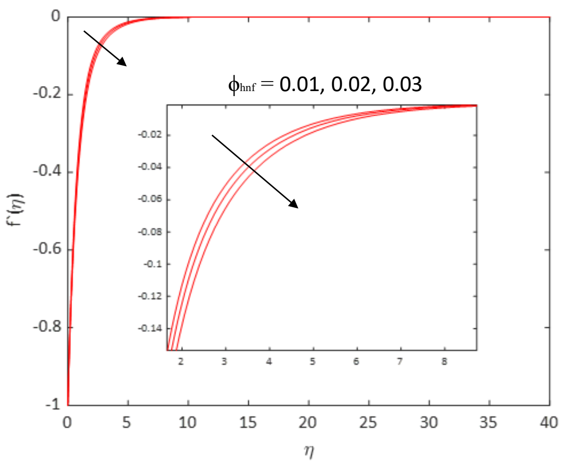

Fig. 12. $f'(\eta)$ for various values of ϕ_{hnf} and Z = -1

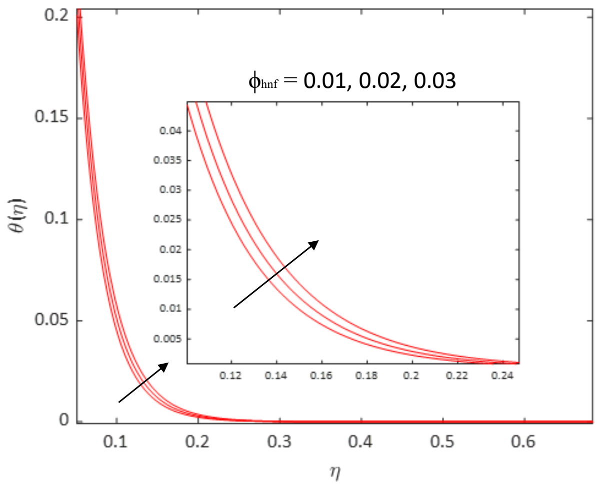

Fig. 13. $\theta(\eta)$ for various values of ϕ_{hnf} and Z = -1

4. Conclusion

In the present study, the Reiner-Philippoff model with mixed convection of hybrid GO-MoS_2/EO nanofluid flow past a shrinking sheet is established. The bvp4c function in the MATLAB programme was used to numerically solve the nonlinear ordinary differential equations (ODE) with the transformed boundary conditions. The results validation was carried out in a few specified cases when the comparison between the current results and the previous results was excellent. The findings for the present problem are as follows:

i. Hybrid nanofluid GO-MoS_2/EO has greater skin friction coefficient and heat transfer rate compared to nanofluids (MoS_2+EO) and (GO+EO), and regular EO.
ii. The increase in local Nusselt number and the decrease in skin friction coefficient were both influenced by an increasing in λ (Reiner-Philippoff parameter) and remain unchanged at λ=1 (Newtonian fluid).
iii. In term of velocity and temperature profile, the rising in λ reduces the velocity of the fluid and enhance the temperature profiles.
iv. The increasing behavior in velocity profile is also observed with the increasing of S (mass flux parameter) and Z (mixed convection parameter), but the temperature profiles show a contradictory behavior.
v. The enhance of volume fraction of hybrid nanofluid (ϕ_{hnf}) will decrease the velocity and increase the temperature profiles.

In addition, the current model can be expanded to include other geometries for a wide range of future applications, including engineering processes like cooling and heating in electrical devices, vehicle radiators (engine cooling systems), nuclear reactors, solar collectors, and heat exchangers. Furthermore, this problem can be simulated in a channel via a vertical plate with various boundary conditions, such as Newtonian heating. Various other techniques can also be used to answer the aforementioned issues accurately.

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