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Research Article

A comparative exploration of a magnetized power-law fluid past an inclined plate with variable physical properties

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ABSTRACT

The present investigation specifically focuses on the reasons behind the changing physical properties of fluid on magnetized Ostwald-dewaele power-law fluid flow towards an inclined plate. In addition to that, the combined impact of viscous and Ohmic heating is incorporated in this study. The governing equations are modified into the dimensionless form using relevant similarity variables. The resultant equations will be numerically solved by implementing the Bvp4c technique (an inbuilt function in MATLAB software). To ensure the accuracy and validity of these results compared with existing literature. Important results are discussed for the two special cases of power-law fluids such as pseudoplastic (Case-1) and dilatant fluids (Case-2). An increment in thermal conductivity raised the velocity and temperature in both shear thickening and shear thinning fluids. Similarly, variable viscosity diminishes the velocity profile. These results may help to provide a better theoretical understanding of various scientific research and engineering applications, especially in thermal energy storage, polymer extrusion processes, petroleum reservoirs, recoverable systems, and cooling of an infinite metallic plate.

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INTRODUCTION

Over a decade, non-Newtonian fluids had a wide range of potential applications in numerous engineering fields which include food processing, polymer, chemicals, paint and adhesives, nuclear reactors, drilling rigs, petroleum, and cooling systems [1]. One of the most commonly used non-Newtonian models is the Ostwald-dewaele power-law fluid [2]. Guha and Pradhan [3] examined the free convection flow of power-law fluids along a plate to explore more insights into power-law fluid. They found that pseudo plastic fluid case plays a predominant compared to dilatant fluid. Recently, Mustafa et al. [4] analyzed a non-similar solution in the study of Ostwald-dewaele power-law fluid flow in the existence of suction along a moving wedge.

The analysis of mass and heat transmission in a mixed convective Ostwald-de waele fluid towards an inclined plate in the existence of a porous medium has recognized a special focus because of its extensive range of applications in energy-related engineering challenges which covers both

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polymer and metal sheets. Recently, the quadratic convective Ostwald-dewaele power-law fluid flow past an inclined plate in the existence of suction and activation energy was analyzed by Naveen and Ram Reddy [5].

Further, the combined effects of Ohmic heating and dissipative effect play a vital role in numerous fields. The synthesis of materials by ejection, electronic chip cooling, and paper manufacturing are a few practical applications where the ultimate product of essential attributes extends through the cooling rate [6]. Rafael Cortell [7] studied the dissipative effects on Ostwald-de-waele fluid through a permeable plate with suction and radiation. Recently, the role of Ohmic heating on magnetized fluid flow along a stretching surface was examined by Sharma and Rishu Gandhi [8], and they found that enhancing the magnetic effects slows down the velocity profile.

Most of the existing literature was studied with the assumption that the physical features of the fluid were constants. However, the existence of temperature may lead to significant fluctuations in the physical characteristics of the fluid flow, particularly in fluid viscosity, electric conductivity, and thermal conductivity of the fluid. It occurs in various technological processes and natural phenomena (e.g., photosynthesis) such as drying crystals, solar ponds, cooling of nuclear reactors, and extrusion of sheets [9-10]. Mahmoud [11] scrutinized the role of variable physical properties on magnetized micropolar fluid towards a stretching surface in the existence of thermal radiation presence. He revealed that the variable thermal conductivity upsurges the temperature distribution. Later, the consequences of variable electrical conductivity and viscosity on magnetized fluid flow towards an inclined heated surface were scrutinized by Mohammad and Salahuddin [12]. Similarly, the impact of variable physical properties on free convective magnetized Casson fluid flow was investigated by Animasaun [13] who pointed out that the velocity and temperature profile enhanced by variable thermal conductivity.

It is clear from the existing literature that, to the best of the author's knowledge, no attempts have been made to investigate the role of variable physical properties of power-law nanofluid flow over an inclined plate. This study illustrates the physical model for various industrial applications such as the chemical processing of heavy metals, thermal energy storage, food and dairy processing, cooling of an infinite metallic plate, and waste treatment.

The present investigation specifically focuses on the reasons behind the changing physical properties of fluid on magnetized Ostwald-dewaele power-law fluid flow towards an inclined plate with a porous medium. Also, the combined impact of viscous dissipation and Ohmic heating are incorporated in this study. The following significant steps will be followed for the accomplishment of the mathematical modeling of the present problem. First, governing equations of Ostwald-Dewaele fluid flow past an inclined plate will be considered under the boundary layer conditions with Boussinesq approximation. Then, the partial differential equations are modified into the dimensionless form by implementing the relevant similarity variables. Later, the resultant equations will be solved by utilizing Bvp4c (an inbuilt function) in MATLAB software. In order to ensure the accuracy and validity of these results compared with existing literature. Finally, the variation of relevant parameters on velocity and temperature distribution has been graphically illustrated. The following question gives deep insight into the current investigation,

- What is the influence of variable physical properties on the flow field?
- How does the magnetic field affect the velocity and temperature distribution?
- Which fluid case plays a dominant role in the flow field?
- How do buoyant force and inclination angle relate to each other?
- What impact does the presence of a porous material have on fluid flow?

The answer to these questions will be beneficial in providing a better theoretical understanding of various scientific research and engineering applications, especially in thermal energy storage, polymer extrusion processes, recoverable systems, petroleum reservoirs, chemical processing of heavy metals, and cooling of an infinite metallic plate.

MATHEMATICAL MODELING

Consider the time-independent flow of magnetized Ostwald-dewaele power-law fluid towards an inclined plate. Cartesian coordinate x-axis is carried along the plate which is inclined from the vertical with an acute angle γ calculated in the rightward. Another axis (y-axis) is normal to it. Also, the frictional effect and Ohmic heating effect are incorporated. Let u_w be the velocity at the wall, T_w and T_∞ be the temperature at the surface and constant ambient temperature. Figure 1 illustrates the physical representation of flow geometry. Further, the fluid physical properties are taken as fixed except for the thermal conductivity, viscosity, and electrical conductivity.

The fluid viscosity [$\mu(T)$] as well as thermal conductivity [$K(T)$] are considered to fluctuate linearly with temperature as follows [9,13]:

$$\mu(T) = \mu_f(1 + \tilde{\beta}(T_w - T)) \text{ likewise, } k^*(T) = k_f(1 + \delta^*(T - T_\infty))$$

Here, k_f and μ_f denotes the constant thermal conductivity and viscosity away from the plate, with constants $\tilde{\beta}$ and δ^*.

The variable transverse magnetic effect is applied to the y direction and expressed as follows (non-uniform magnetic field applied) $B(x) = B_0/\sqrt{x}$ with a constant B_0. Additionally, the electric conductivity is taken as the velocity-dependent form $\bar{\sigma} = \sigma u$ with a constant σ (Ref. Mohammad and Salahuddin [12]).

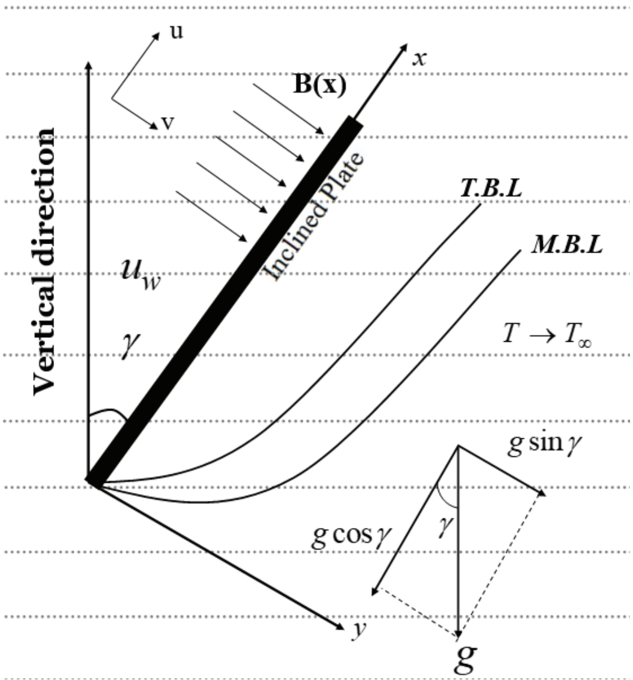


Figure 1. Flow geometry.

Based on the aforementioned assumptions, the governing equations are formulated as follows [14-16]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\rho_f\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{\partial}{\partial y}\left(\mu(T)\left(\frac{\partial u}{\partial y}\right)^n\right) + g\rho_f\beta_T\cos\gamma(T - T_\infty) - \bar{\sigma}\left(B(x)\right)^2 u - \frac{\mu(T)}{k_p}u \quad (2)$$

$$\left(\rho c_p\right)_f\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{\partial}{\partial y}\left(k^*(T)\frac{\partial T}{\partial y}\right) + \mu(T)\left(\frac{\partial u}{\partial y}\right)^{n+1} + \bar{\sigma}\left(B(x)\right)^2 u^2 \quad (3)$$

Here, (u, v) is the velocity components in the (x, y) direction.

Also, boundary conditions that are associated with the present problem are [15,17],

$$v = 0;\ u = u_w;\ T = T_w \ \text{as} \ y \to 0$$
$$u \to 0;\ T \to T_\infty \ \text{as} \ y \to \infty \quad (4)$$

Dimensionless Analysis

The similarity transformations of the current study are (Ref. Nandy [14]):

$$\eta = y\left(\frac{a^{2-n}}{\nu_f}\right)^{\frac{1}{n+1}} x^{\frac{1-n}{n+1}};\ \psi = \left(\frac{\nu_f}{a^{1-2n}}\right)^{\frac{1}{n+1}} x^{\frac{2n}{n+1}} f;\ \theta = \frac{\left(T - T_\infty\right)}{\left(T_w - T_\infty\right)} \quad (5)$$

Stream function (ψ) will automatically satisfy Eq.(1) through $u = \frac{\partial\psi}{\partial y}$, $v = -\frac{\partial\psi}{\partial x}$ and the velocity components are transformed into

$$u = axf'(\eta);\ v = -\left(\frac{a^{1-2n}}{\nu_f}\right)^{\frac{-1}{n+1}}\left(\eta\frac{1-n}{n+1}f'(\eta) + \frac{2n}{n+1}f(\eta)\right)x^{\frac{n-1}{n+1}}; \quad (6)$$

Using transformation Eq (5) and (6), Eq (2)-(4) are reduced into dimensionless form as follows,

$$\left[1+\delta_1\left(1-\theta\right)\right]\left[n\left(f''\right)^{n-1}f''' - Kf'\right] - \delta_1\left(f''\right)^n\theta' - \left(1+M\right)f'^2 + \left(\frac{2n}{n+1}\right)ff'' + \left(\lambda\cos\gamma\right)\theta = 0 \quad (7)$$

$$\left(1+\delta_2\theta\right)\theta'' + \delta_2\left(\theta'\right)^2 + \Pr\left\{\left(\frac{2n}{n+1}\right)f\theta' + \left[1+\delta_1\left(1-\theta\right)\right]Ec\left(f''\right)^{n+1} + M\,Ec\left(f'\right)^3\right\} = 0 \quad (8)$$

The conditions Eq. (4) are reduced into:

$$f(0) = 0;\ \theta(0) = 1;\ f'(0) = 1;\ f'(\infty) \to 0;\ \theta(\infty) \to 0 \quad (9)$$

The dimensionless parameters that are included in the above equations such as variable viscosity parameter (δ_1), generalized Prandtl number (Pr), permeability parameter (K), Eckert number (Ec), Mixed convection parameter (λ) with the case of opposing flow ($\lambda < 0$), forced convection ($\lambda = 0$) and assisting flow ($\lambda > 0$), variable thermal conductivity parameter (δ_2), are described as follows:

$$K = \frac{\nu_f}{k_p a};\ \delta_2 = \delta^*\left(T_w - T_\infty\right);\ \lambda = \frac{Gr_x}{Re_x^2};\ Gr_x = \frac{g\beta_T E_1^2 (T_w - T_\infty)x^3}{\nu_f^2};$$

$$Re_x = \frac{a^{2-n}x^2}{\nu_f};\ \delta_1 = \tilde{\beta}\left(T_w - T_\infty\right);\ M = \frac{\sigma B_0^2}{\rho_f};$$

$$\Pr = \frac{\nu_f}{\alpha_f a^{1-n}}Re_x^{\frac{n-1}{n+1}};\ E_1 = \frac{1}{a^{n-1}};\ Ec = \frac{u_w^2}{c_p(T_w - T_\infty)};$$

In addition, the friction drag coefficient $C_f\left(C_f = 2\tau_w / \rho_f u_w^2\right)$ and Nusselt number $Nu_x\left(Nu_x = xq_w / k_f(T_w - T_\infty)\right)$ at the plate are expressed in dimensionless form by using Eq(5)-(6) as (Ref. Nandy [14]):

$$\left(\mathrm{Re}_x\right)^{\frac{1}{n+1}}C_f = 2E_1\left(f''(0)\right)^n \text{ and } \left(\mathrm{Re}_x\right)^{\frac{-1}{n+1}}Nu_x = -\theta'(0). \quad (10)$$

RESULTS AND DISCUSSION

The resultant equations (7)-(8) along with corresponding conditions (9) are extremely complex and highly non-linear. Therefore, it might not be possible to find a closed form of the solution; in such case, the Bvp4c technique (an inbuilt function in MATLAB software) was implemented for numerical simulation. The Bvp4c package is a technique for dealing with boundary value problems. This software utilizes the finite difference approach, which applies the three-stage Lobatto (IIIa) formula [18]. The solution can be obtained by providing an initial guess at an initial mesh point and then varying the step size to get the required precision. Further, the outcomes of $\theta'(0)$ are validated by the previous works of Grubka and Bobba [19], and Chen [20] which are listed in Table 1.

Similarly, the outcomes of $f''(0)$ are validated by the existing works of exact solutions of Turkyilmazoglu [22] and Hayat [21] which are displayed in Table 2.

A comprehensive graphical comparison is generated between the characteristics of pseudoplastic fluid $n < 1$ (*Case-I*) and dilatant fluid $n > 1$ (*Case-II*) of the Ostwald-dewaele power-law fluid. Also, graphs are depicted for different values of K, λ, M, Ec, δ_1, δ_2 and γ to determine the intensity of these parameters on f' and θ. For this investigation, the fixed values of all parameters are regarded as $K=M=0.5$, $Ec=0.3$, $\gamma=45^o$, $\delta_1=\delta_2=1$, $\lambda= 0.5$, and Pr=1.

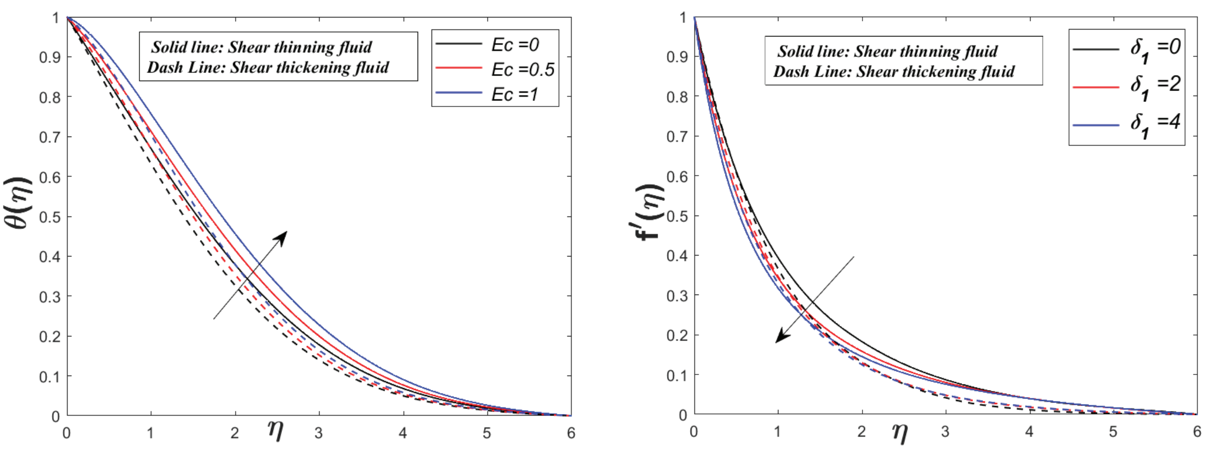
Figure 2(a) reveals the changes in Ec on θ. The temperature distribution (θ) enhanced for higher values of Ec

Table 1. Validation of current results of $\theta'(0)$ with distinct values of Pr and n=1 with the absence of other parameters

Pr	Grubka and Bobba [19]	Chen [20]	Present results
0.7	-0.4631	−0.46315	-0.462573
1	-0.5820	−0.58199	-0.583865
3	-1.1652	−1.16523	-1.165018
10	-2.3080	−2.30796	-2.307853
100	-7.7657	-	-7.765537

Table 2. Validation for current results of $f''(0)$ with distinct K values and n=1 with the absence of other parameters

K	Hayat [21]	Turkyilmazoglu [22]	Present results
0	-1.000000	-1.0000000	-1.000484
0.5	-1.224747	-1.22474487	-1.224776
1	-1.414217	-1.41421356	-1.414216
1.5	-1.581147	-1.58113883	-1.581139
2	-1.732057	-1.73205081	-1.732051



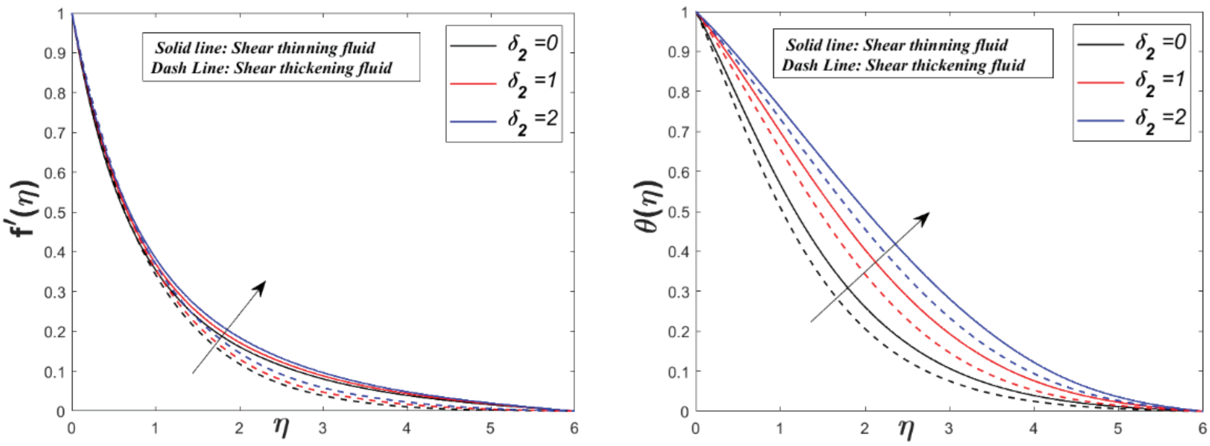
(a) (b)

Figure 2. (a) variation of Ec on θ, (b). variation of δ_1 on f'.

in both *Case I* and *Case II*. Physically, the Eckert number is carried out by the dissipation term and the Joule heating term in the energy equation respectively. Due to these effects, the electrical and mechanical energy converts into thermal energy through internal fluid friction and magnetic resistance. As a result, a sudden rise in the *Ec* parameter enhances the temperature distribution θ. This outcome is quantitatively similar to the recent works of Akinbo and Olajuwon [23].

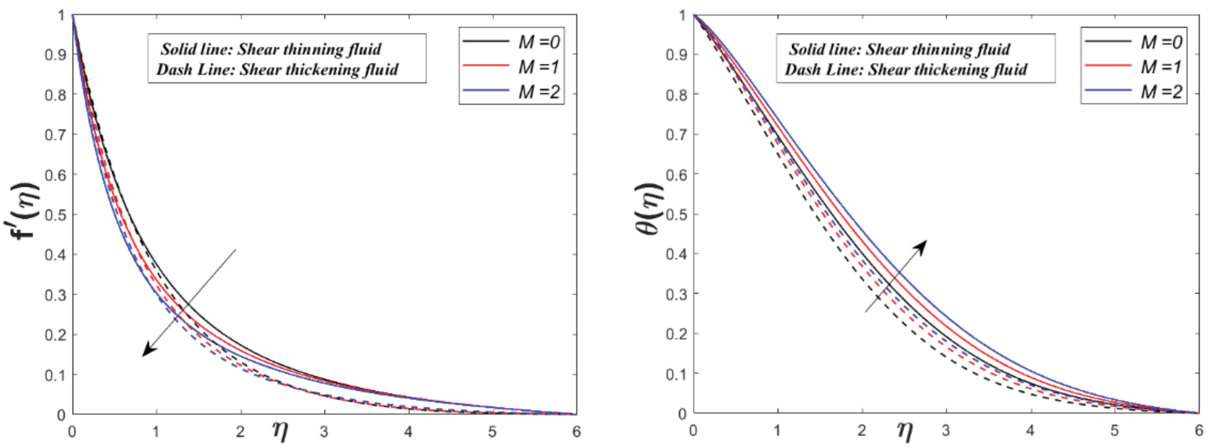
The influence of variable viscosity (δ_1), on f' depicted in Figure 2(b). Increasing δ_1 values lead to a reduced velocity profile (f') and the pseudoplastic fluid is more predominant compared to dilatant fluids with this parameter. These results have acceptable agreement with the recent works of Sathya and Naveen[18]. This kind of outcome will be beneficial in the highly viscous fluids with weak thermal conductivity as well as in various lubrication industries.

From Figures 3(a)-3(b), variable thermal conductivity (δ_2) variations on f' and θ is illustrated. The curve $\delta_2 = 0$ symbolizes the constant thermal conductivity. An increment in δ_2 values enhance both velocities f' (in Figure 3(a)) and temperature profiles θ (in Figure 3(b)). These results have a good agreement with the recent works of Mahmoud [10]. However, the pseudoplastic fluids are more predominant in f' comparison to dilatant fluids because pseudoplastic has less apparent viscosity at greater shear rates. Figures 4 (a)-5(b) demonstrate the inclination angle of plate (γ) and magnetic parameter (M) variations on f' and θ. For higher values of M and γ, the f' diminishes, and the reverse behavior is noticed in the temperature. Physically, raising the values of M produces a stronger resistive effect called Lorentz force that reduces the fluid motion by producing thermal energy. As a result, temperature is enhanced in Figure 4(b) and velocity diminished in Figure 4(a). These results are in noteworthy agreement with the existing work of Akbari



(a) (b)

Figure 3. Variation of δ_2 on (a) f' (b) θ for both types of fluid.



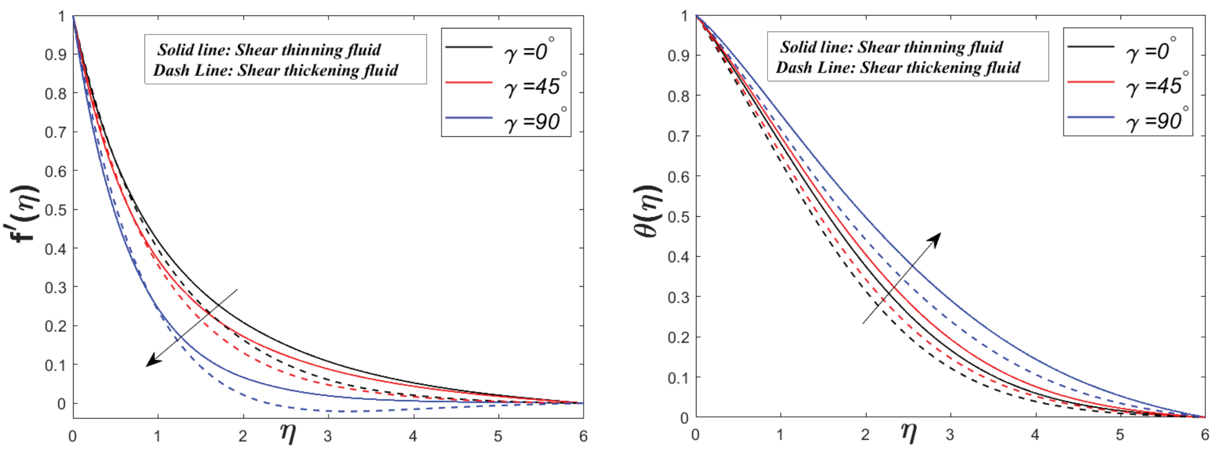
(a) (b)

Figure 4. Variation of M for both types of fluid on (a) f' (b) θ.

et al. [24]. Similarly, an inclination angle γ and buoyancy force have an inverse relationship. So, variation reduces the buoyancy force which leads to an enhanced temperature profile (in Figure 5(b)) and resists the fluid motion (in Figure 5(a)). This kind of outcome would be beneficial in the theoretical understanding of engineering problems including metallurgical processes, Magnetohydrodynamic (MHD) generators, fusion reactors, and magnetic actuators and sensors.

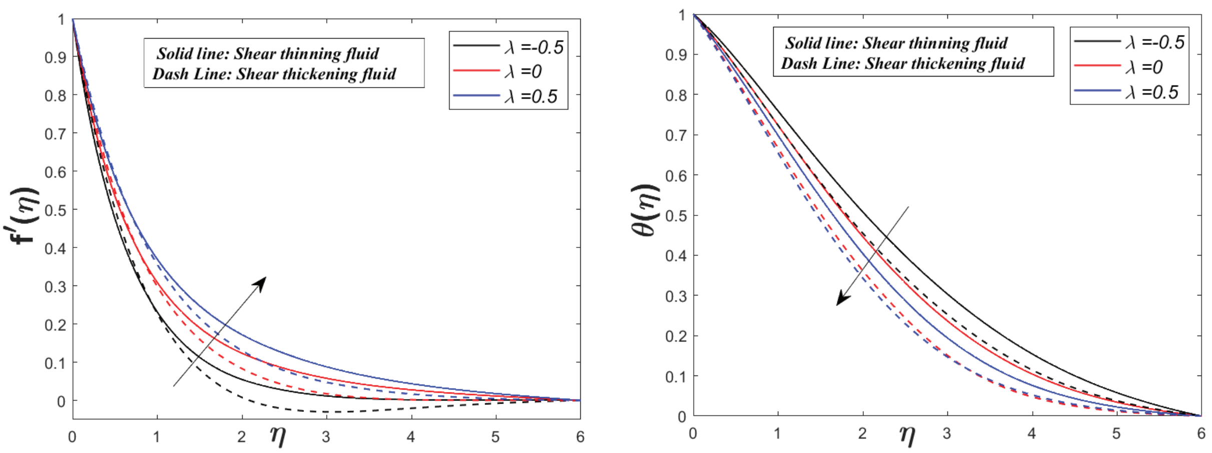
Figures 6(a)-6(b) exhibit the variation of mixed convection parameter (λ) for both types of fluids on f' and θ. An increment in values of λ leads to enhanced velocity (f') but the temperature distribution (θ) exhibits the opposite behavior for both cases. The domination of pseudoplastic fluid and dilatant fluid on f' and θ is also noticed. Physically, increasing values lead to generating a large amount of buoyancy force which gives rise to fluid motion (f') in Figure 6(a). At the same time, it increases the difference among temperature at the surface and fluid temperature which slowdowns the temperature (θ) in Figure 6(b). These results are in good agreement with the works of Ram Reddy et al. [25-26].

The variation of the values of K on f' and θ depicted in Figures 7(a)-7(b). An increment in K values reduces the velocity (f') . At the same time, it upsurges the temperature profile (θ) in Figure 7(b) for *Case I and Case II*. It is interesting to observe that the boundary layer thickness is higher in the case of pseudoplastic fluid. Physically, higher values of K lead to resist the flow motion which slows down the velocity profile (f') in Figure 7(a).



(a) (b)

Figure 5. Variation of γ for both types of fluid on (a) f' (b) θ.



(a) (b)

Figure 6 . Variation of both fluid types on (a) f' (b) θ.

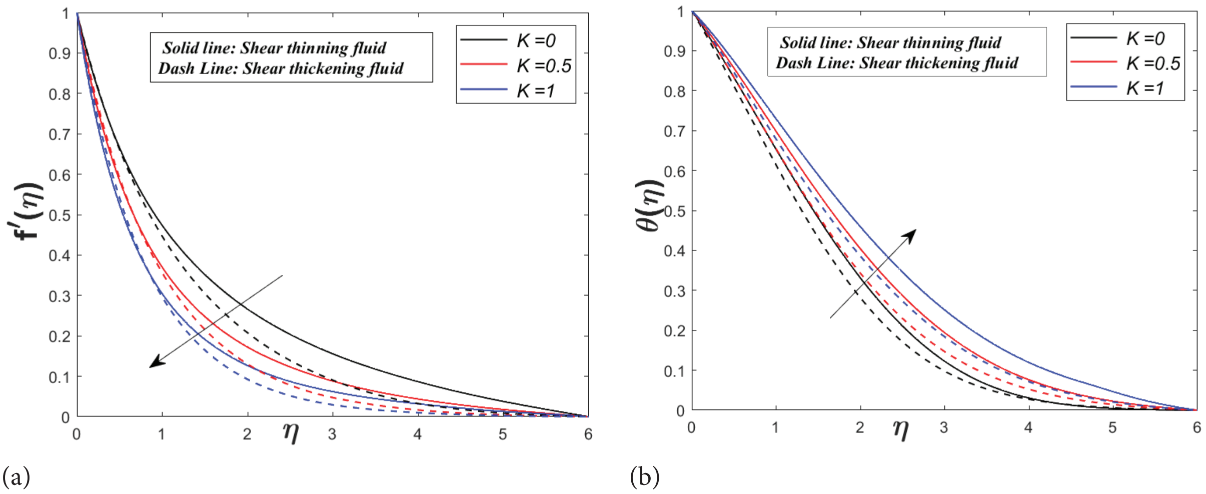


Figure 7. Variation of K for both types of fluid on (a) f' (b) θ.

CONCLUSION

The magnetized Ostwald-dewaele fluid towards an inclined plate with a porous medium is investigated. Further, we have incorporated variable physical properties of viscosity, and electrical and thermal conductivity which helps in the theoretical understanding of the applications including cooling of nuclear reactors and extrusion of sheets. Furthermore, the combined impact of frictional effect and Ohmic heating are also considered. Summarizing the current generated results may be beneficial to numerous researchers in assisting the results of the mathematical simulation to be as similar to the actual scenario as possible. Some significant observations are pointed out below:

- An increment in variable viscosity effect diminishes the velocity profile of both pseudoplastic and dilatant fluid.
- Temperature upsurges and velocity diminishes for larger permeability and Magnetic parameters.
- The viscous effect and variable thermal conductivity enhance temperature. The pseudoplastic fluid is more predominant compared to the dilatant fluid.
- Due to buoyancy force, an inclination angle diminishes the velocity profile; however, this effect has a greater impact on shear-thinning fluid than on shear-thickening fluid.

These results may help to provide a better theoretical understanding of various scientific research and engineering applications, especially in thermal energy storage, polymer extrusion processes, recoverable systems, petroleum reservoirs, and cooling of an infinite metallic plate.

Future Scope

This work may be extended to include different kinds of nanofluids based on various boundary conditions, which will be specifically in the cooling of electrical appliances.

AUTHORSHIP CONTRIBUTIONS

The authors of this work each contributed equally.

CONFLICT OF INTEREST

No conflicts of interest have been disclosed by the authors.

ETHICS

There are no ethical issues with the publication of this manuscript.

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