

Variable Viscosity Effect on MHD Falkner–Skan Axisymmetric Ethanol Boundary-Layer Flow over a Wedge with Viscous Dissipation

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Abstract. The present work investigates the influence of temperature-dependent viscosity on steady forced convection and axisymmetric laminar flow of ethanol in the presence of a magnetic field and viscous dissipation. The governing nonlinear, coupled PDE's, together with the associated boundary conditions, are transformed into a system of non-dimensional ODE's through non-similar transformations. The resulting equations are solved numerically using an implicit finite difference scheme combined with the quasilinearization technique. The computed solutions are presented graphically to assess the effects of variable viscosity and viscous dissipation on the skin friction and heat transfer characteristics. Furthermore, the influence of the magnetic field on skin friction, velocity distribution, heat transfer rate, and temperature profile is analyzed. The role of wall–fluid temperature difference on skin friction and heat transfer is also examined

1 Introduction

The analysis of steady laminar flow around a wedge-shaped geometry was initially carried out by Falkner and Skan [1], demonstrating the implementation of Prandtl's principles in boundary layer studies. Subsequently, Hartree [2] further extended the present investigation utilizing similarity transformations and provided computed numerical values of wall shear stress corresponding to various wedge angles. Eckert [3] contributed by solving the Falkner-Skan flow over an isothermal wedge and was the earliest to present heat transfer wall values. Stewartson [4] further explored solutions to the Falkner-Skan equation. Subsequently, a variety of researchers have derived solutions addressing various features of this type of boundary layer scenarios [[5],[6],[7],[8],[9],[10],[11]].

In modern years, magnetohydrodynamic (MHD) boundary layer flows have attracted significant attention due to their mathematical complexity and physical relevance. Vajravelu and Nayfeh [12] investigated hydromagnetic convection over a cone and a wedge. Similarly, Kafousias and Nanousis [13] studied MHD flow past a wedge with injection and suction effects. Most Recently, Abbasbandy and Hayat [14] proposed analytical methods for the magneto hydrodynamic Falkner-Skan flow. Moreover, contemporary studies have focused on natural and mixed convection phenomena in annular geometries, incorporating viscous dissipation and internal heating effects, as reported by Sankar et al.,[15] and Girish et al.,[16] highlighting the importance of energy dissipation in convection-dominated flows.

The characteristics of laminar forced convection boundary layers are strongly governed by fluid viscosity and thermal conductivity. Variations in these thermo-physical properties can substantially alter the relations among boundary layer and the solid surface. Since both viscosity and thermal conductivity are temperature dependent, their influence is most effectively introduced

by imposing a temperature variation among the wall and the surrounding fluid. From a practical standpoint, wall heating is often employed to steady the boundary layer and delay the onset of flow separation, particularly in cases where viscosity diminishes with rising temperature. For engineering and technological applications, surface heating therefore provides a useful means of controlling boundary layer behavior by modifying the coupled effects of thermal diffusion, temperature-dependent viscosity, and momentum transport in the near-wall region. Recent work by Fatima and Rama Prasad [17] demonstrated the combined influence of temperature-dependent viscosity, chemical reaction, and internal heat generation in MHD flows, underscoring the relevance of coupled thermal and momentum transport mechanisms in advanced fluid systems. The influence of variable viscosity in magneto hydrodynamic flow configurations have been widely investigated in recent literature, particularly for non-Newtonian and electrically conducting fluids [18].

In this study, we analyze the effect of changing viscosity, viscous dissipation, magnetic hydrodynamics (MHD), and the Prandtl number on steady, laminar, and ethanol flow under incompressible boundary layer conditions over an axisymmetric body, specifically a wedge. It is noteworthy that ethanol, primarily obtained through molasses processing in sugarcane production, is an environmentally friendly biofuel. Moreover, ethanol is among the most widely used fluids after water in engineering applications, especially in the automotive and pharmaceutical industries. The present results are relevant to ethanol-based cooling systems, biofuel processing, and MHD thermal control in chemical reactors, where temperature-dependent viscosity and viscous dissipation significantly influence heat transfer efficiency.

Viscous dissipation plays a dominant role in high-speed flows, highly viscous fluids, and flows subjected to strong magnetic fields, where internal frictional heating alters the thermal activities of the fluid. The existence of viscous dissipation can lead to a substantial increase in fluid temperature near the wall and, for particular parameter regimes, may even cause a reversal in the heat transfer direction.

2 Mathematical Analysis

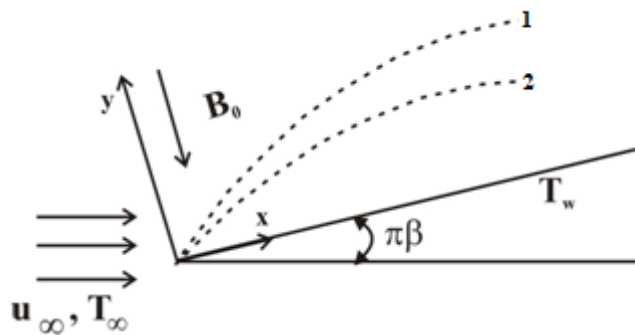


Figure 1. MHD Falkner-Skan wedge flow coordinate system and physical model, where one and two stand for the thermal and momentum boundary layer edges, respectively.

The physical configuration of the present investigation (see Fig. 1) employs of a Cartesian coordinate system in which x is measured along the surface of the wedge and y is taken perpendicular to it. We believe the steady, two-dimensional laminar boundary layer flow of electrically conducting, an incompressible fluid moving near the wedge with velocity u_∞ . The wall temperature T_w is assumed to be constant and uniform, and is higher than the free-stream temperature T_∞ . A transverse magnetic field of strength B_0 is imposed perpendicular to the wedge surface. It is further assumed that the magnetic Reynolds number is low, so that the induced magnetic field can be neglected.

Since ethanol is incompressible, the heat generated due to compression is not important. In order to maintain the temperature variation among the wall and the free stream within the range (0–40°C), the ambient fluid temperature is fixed at $T_\infty = 28.7^\circ\text{C}$ and the temperature difference between the wall and the ambient fluid is taken as $\Delta T_w = 10^\circ\text{C}$. It is observed that the variation of density (ρ) and specific heat (C_p) of ethanol with temperature is less than one percent (see

Table 1); therefore, these properties are treated as steady.

Nonetheless, due to the notable dependence of thermal conductivity k and viscosity μ (and thereby the Prandtl number (Pr)) on temperature, both viscosity and the Prandtl number are modeled as inversely proportional to temperature in a linear relationship [19, 20].

$$\text{Pr} = \frac{1}{c_1 + c_2 T}. \quad (2.1)$$

$$\mu = \frac{1}{b_1 + b_2 T}, \quad (2.2)$$

$$b_1 = 53.804, \quad b_2 = 1.584, \quad c_1 = 0.0428, \quad c_2 = 0.0006. \quad (2.3)$$

Table 1. Thermal and physical characteristics of ethanol across various temperatures [14]

Temperature (°C)	Prandtl number (Pr)	Viscosity μ (gr. $\times 10^{-2}$ cm s)	Thermal conductivity k (erg $\times 10^5$ /cms K)	Specific heat C_p (J $\times 10^7$ /kg K)	Density ρ (gr./cm ³)
0	23.090	1.7731	0.1722	2.2417	0.8038
10	20.106	1.4664	0.1704	2.2420	0.7982
20	17.45	1.2002	0.1671	2.4284	0.7902
30	13.75	1.0036	0.1612	2.5297	0.7822
40	12.63	0.8385	0.1575	2.3243	0.7742
50	11.87	0.7063	0.1480	2.1227	0.7636

The correlations are developed using data reported in reference [21]. Equations (2.1) and (2.2) offer reasonably precise estimates for liquids like ethanol, especially when the temperature differences among the wall and the surrounding environment are minute.

Under these hypotheses, the governing boundary layer equations for the steady forced convection in MHD Falkner-Skan wedge flow are expressed as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (2.4)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{1}{\rho} \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) - \frac{\sigma B_0^2}{\rho} (u - U), \quad (2.5)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{1}{\rho c_p} \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\mu}{\rho c_p} \left(\frac{\partial u}{\partial y} \right)^2. \quad (2.6)$$

The conditions at the boundary are précised by

$$\begin{aligned} \text{at } y = 0 : \quad & u = v = 0, \quad T = T_w, \\ \text{as } y \rightarrow \infty : \quad & u \rightarrow U(x) = u_\infty \left(\frac{x}{L} \right)^m, \quad T \rightarrow T_\infty, \\ \text{at } x = 0 : \quad & T = T_\infty, \quad \text{and} \quad u = u_\infty. \end{aligned} \quad (2.7)$$

Further,

$$\begin{aligned} u &= \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x}. \\ f(\eta) &= \sqrt{\frac{1+m}{2}} \frac{L^m}{\nu u_\infty} \left(\frac{\psi}{x^{(1+m)/2}} \right), \\ \eta &= \sqrt{\frac{1+m}{2}} \frac{u_\infty}{\nu L^m} \left(\frac{y}{x^{(1-m)/2}} \right), \quad G(\eta) = \frac{T - T_\infty}{T_w - T_\infty}. \end{aligned} \quad (2.8)$$

Incorporating the transformations from Eqs. (2.4)–(2.6) into the preceding equations leads to

$$(NF')' + \frac{2m}{1+m} (1 - F^2) - \frac{2}{1+m} M(F - 1) + fF' = 0, \quad (2.9)$$

$$\left(NPr^{-1}G'\right)' + G'f + NE_cF'^2 = 0. \quad (2.10)$$

Here,

$$\frac{u}{u_e} = f' = F, \quad f = \int_0^\eta F d\eta.$$

$$v = -\sqrt{\frac{2}{1+m}} \left(\frac{\nu u_\infty}{L^m}\right) x^{(m-1)/2} \left[\frac{m+1}{2}f + \eta f' \frac{m-1}{2}\right].$$

$$N = \frac{\mu}{\mu_\infty} = \frac{b_1 + b_2 T_\infty}{b_1 + b_2 T} = \frac{1}{1 + a_1 G}, \quad \text{where } a_1 = \left(\frac{b_2}{b_1 + b_2 T_\infty}\right) \Delta T_w.$$

$$Pr = \frac{1}{c_1 + c_2 T} = \frac{1}{a_2 + a_3 G},$$

with

$$a_2 = c_1 + c_2 T_\infty, \quad a_3 = c_2 \Delta T_w, \quad \Delta T_w = (T_w - T_\infty). \quad (2.11)$$

It is further observed from Eqs.(2.9) that the parameter m is related to the wedge apex angle $\pi\beta$ through the classical Falkner–Skan relationship

$$m = \frac{\beta}{2 - \beta} \quad \text{or equivalently} \quad \beta = \frac{2m}{m + 1}.$$

After transformation, the boundary conditions become:

$$F = 0, \quad G = 1 \quad \text{at } \eta = 0,$$

$$F = 1, \quad G = 0 \quad \text{as } \eta \rightarrow \infty. \quad (2.12)$$

Here, ψ and f denote the dimensional and dimensionless stream functions, respectively. The parameter m represents the Falkner–Skan wedge power-law parameter. The functions G and F correspond to the dimensionless temperature and velocity of the fluid, respectively, while Pr denotes the Prandtl number. A prime (') indicates differentiation w.r.to the similarity variable η .

The engineering quantities of practical interest, namely the skin friction coefficient and the local Nusselt number characterizing heat transfer, are defined as follows:

$$C_f(Re_L)^{1/2} = \frac{\tau_w}{\frac{1}{2}\rho u_\infty^2} = 2\sqrt{\frac{1+m}{2}} (F')_{\eta=0},$$

$$Nu(Re_L)^{-1/2} = -k \left(\frac{\partial T}{\partial y}\right)_{y=0} \left(\frac{1}{T_w - T_\infty}\right) = -\sqrt{\frac{1+m}{2}} (G')_{\eta=0}. \quad (2.13)$$

Here, the shear wall stress τ_w is expressed as

$$\tau_w = \mu \left(\frac{\partial u}{\partial y}\right)_{y=0},$$

here k is the thermal conductivity and μ is the dynamic viscosity, $Re_L = \frac{u_\infty L}{\nu}$ stand for's the Reynolds local number.

3 Methodology

Applying quasilinearization technique[19, 20], the governing nonlinear PDE's (2.9) and (2.10) are switched into a series of linear equations through an iterative procedure.

$$F^{(k+1)''} + X_1^{(k)} F^{(k+1)'} + X_2^{(k)} F^{(k+1)} + X_3^{(k)} G^{(k+1)} = U_1^{(k)}, \quad (3.1)$$

$$G^{(k+1)''} + Y_1^{(k)} G^{(k+1)'} + Y_2^{(k)} G^{(k+1)} + Y_3^{(k)} F^{(k+1)} = U_2^{(k)}, \quad (3.2)$$

In this formulation, the coefficient functions corresponding to the iteration level k are known from the preceding step, whereas the unidentified functions at the $k + 1$ iteration are to be evaluated.

Consequently, the associated boundary surroundings are modified accordingly.

$$\begin{aligned} F^{(k+1)} &= 0, \quad G^{(k+1)} = 1 \quad \text{at } \eta = 0, \\ F^{(k+1)} &= 1, \quad G^{(k+1)} = 0 \quad \text{at } \eta = \eta_\infty. \end{aligned} \quad (3.3)$$

The coefficients in equations (3.1) and (3.2) are given by

$$\begin{aligned} X_1^{(k)} &= -\frac{a_1}{1 + a_1 G} + (1 + a_1 G) f', \\ X_2^{(k)} &= \frac{2}{1 + m} M(1 + a_1 G) - \frac{2m}{1 + m} + (1 + a_1 G) 2F, \\ X_3^{(k)} &= \frac{a_1'}{1 + a_1 G} F' G + \left(\frac{2m}{1 + m} \right) \left[a_1 (1 - F^2) + a_2 \left(\frac{2m}{1 + m} \right) M(1 - F) \right], \\ U_1^{(k)} &= \frac{2m}{1 + m} (1 + a_1 G) - \frac{2m}{1 + m} (1 + a_1 G) F^2 - \frac{2m}{1 + m} M(1 + a_1 G) + X_3^{(k)} G, \\ Y_1^{(k)} &= -\frac{2a_2 G'}{1 + a_1 G} + 2a_3 G' \text{Pr} + (1 + a_1 G) f' \text{Pr}, \\ Y_2^{(k)} &= \frac{a_1^2 G'^2}{(1 + a_1 G)^2} - a_3^2 G' \text{Pr}^2 + f G (a_2 - a_3) \text{Pr}^2, \\ Y_3^{(k)} &= 2 \text{Pr} Ec F', \\ U_2^{(k)} &= \frac{a_1 G'^2}{1 + a_1 G} + a_3 G' \text{Pr} + \text{Pr} Ec (F')^2 + Y_2^{(k)} G. \end{aligned}$$

Taking into account the central difference discretization scheme in the η -direction is employed to transform Eqs. (3.1) and (3.2), together with the boundary conditions given in Eq. (3.3), into finite difference form. The resulting system is reduced to a set of linear algebraic equations having a block tri-diagonal matrix structure at each iteration level. This system is solved using the procedure outlined in Refs.[22] and [23].

The step size in the η -direction is carefully chosen and fixed at $\Delta\eta = 0.01$ to ensure numerical stability and convergence. The computed results are observed to be independent of further refinement of the step size, maintaining accuracy up to the fourth decimal place. For the numerical computations, the edge of the boundary layer is approximated by taking $\eta_\infty = 5.0$.

To address the nonlinear nature of the governing equations, an iterative procedure is adopted to achieve local linearization. Convergence is monitored by evaluating the relative difference between successive iteration values of the velocity and temperature gradients at the wall. The iterative process is terminated once the prescribed convergence criterion is satisfied when

$$\max \left\{ \left| F_w^{(k+1)'} - F_w^{(k)'} \right|, \left| G_w^{(k+1)'} - G_w^{(k)'} \right| \right\} < 10^{-4}. \quad (3.4)$$

4 Results And Discussion

The numerical computations, which are displayed graphically, concentrate on a variety of values of temperature dependent viscosity, MHD, viscous dissipation and Falkner–Skan parameter (m). We have compared heat transfer (G'_w) values with the results provided by White [9] spanning from $0.1 \leq Pr \leq 3.0$ (see Table 2) using $m = 0$ and 0.2 to assess the validity of the proposed numerical system.

Table 2. Comparison of numerical results of G'_w for various Prandtl numbers when $M = Ec = 0.0$ with those given by White [9]

Pr	White [9]		Present results	
	$m = 0$	$m = 0.2$	$m = 0$	$m = 0.2$
0.1	0.1980	0.2090	0.1978	0.2089
0.3	0.3037	0.3278	0.3028	0.3267
0.6	0.3916	0.4289	0.3911	0.4299
0.72	0.4178	0.4592	0.4151	0.4583
1.0	0.4696	0.5195	0.4695	0.5184
2.0	0.5972	0.6690	0.5977	0.6694
3.0	0.6859	0.7739	0.6851	0.7746

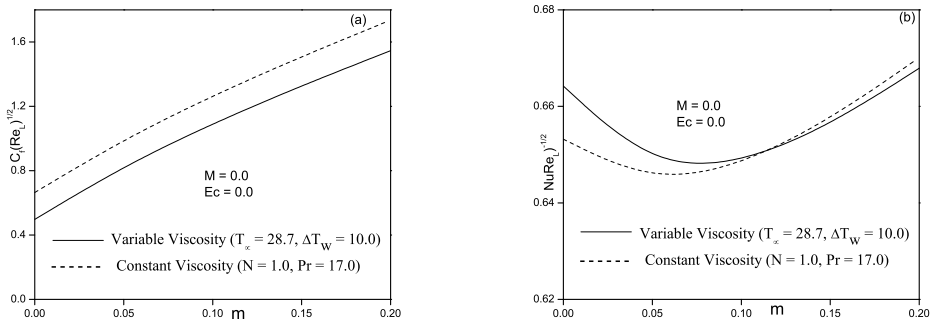


Figure 2 Comparison of results for variable fluid properties versus constant fluid properties: (a) Skin friction coefficient (b) Heat transfer coefficient

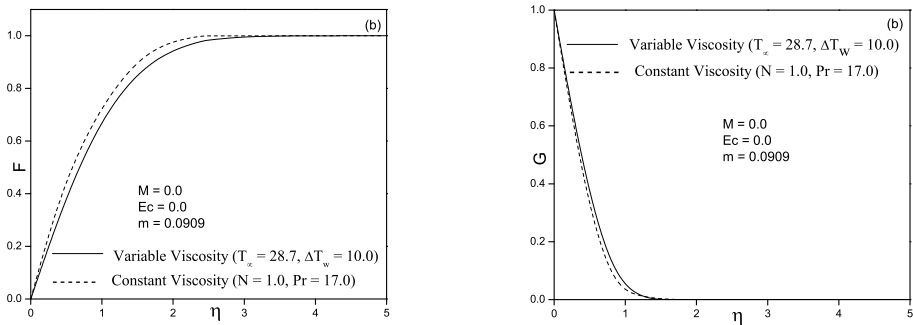


Figure 3 Comparison of results for inconsistent fluid properties versus steady fluid properties: (a) Velocity and (b) Temperature profiles.

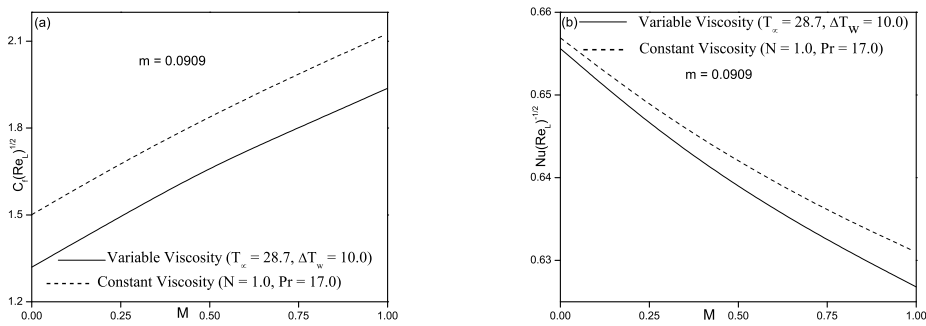


Figure 4. Comparison of results for variable fluid properties versus steady properties of fluid: (a) Skin friction coefficient (b) Heat transfer coefficient

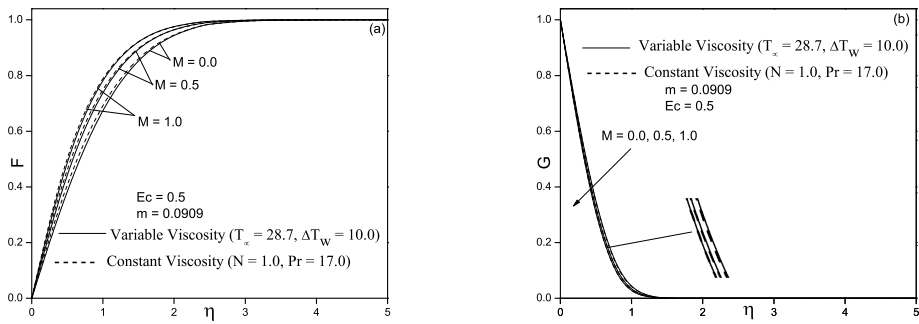


Figure 5 (a) Velocity and (b) Temperature profiles for varying magnetic field values

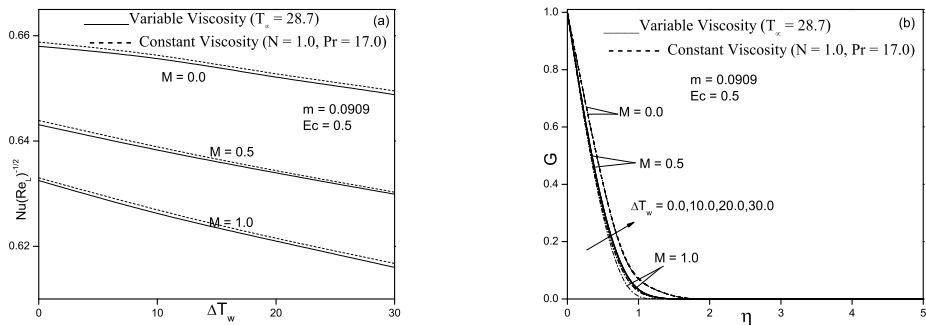


Figure 6 (a) Heat transfer and (b) Temperature profiles corresponding to various Magnetic field parameters With ΔT_w

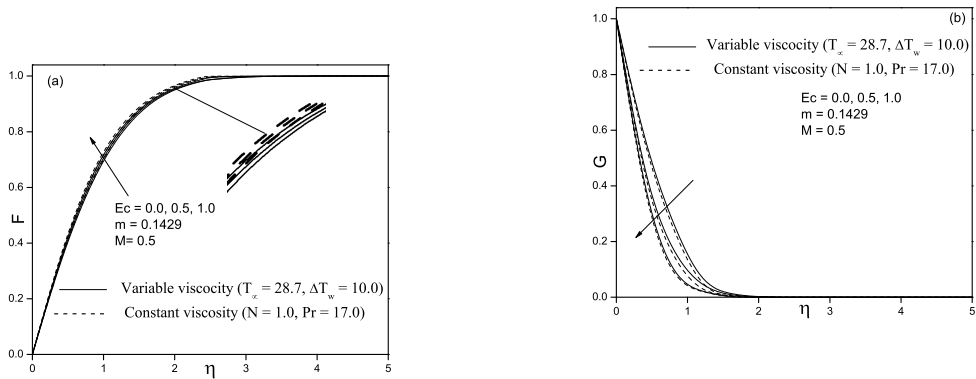


Figure 7 (a) Velocity and (b) Temperature profiles corresponding to various Eckert number (Ec) values.

The numerical computations, which are displayed graphically, concentrate on a variety of values of temperature dependent viscosity, MHD, viscous dissipation and Falkner–Skan parameter (m). We have compared heat transfer $[Nu(Re_L)^{-1/2}]$ values with the results provided by White [9] spanning from $0.1 \leq Pr \leq 3.0$ (see Table 2) using $m = 0$ and 0.2 to assess the validity of the proposed numerical scheme.

Figure 2 describe the result of Prandtl number and inconsistent viscosity on the heat transfer $[Nu(Re_L)^{-1/2}]$ and skin friction $[C_f(Re_L)^{1/2}]$ coefficients at different m . This diagram also consists outcomes for $Nu(Re_L)^{-1/2}$ and $C_f(Re_L)^{1/2}$ when $Pr = 17.0$ and $N = 1$ at room temperature $T = 20^\circ\text{C}$ for constant Prandtl number and viscosity.

From Fig. 2(a), it is evident that $C_f(Re_L)^{1/2}$ escalates from an initial value of nil to a peak value within a specific sort of m ($m = 0.2$). Additionally, the non-constant fluid properties are observed to enhance $C_f(Re_L)^{1/2}$ while reducing the heat transfer coefficient, as illustrated in Fig. 2(b).

The coefficient of skin friction ($C_f(Re_L)^{1/2}$), in the existence of changeable fluid properties, varies from the scenario with stable fluid characteristics approximately 17.37% at $m = 0.1$. Conversely, the percentage difference in the heat transfer coefficient, $Nu(Re_L)^{-1/2}$, differentiating constant and varying fluid attribute is 1.1% at $m = 0.0$ and 0.03% at $m = 0.1$.

The quantitative analysis provided highlights that the impact of changing fluid characteristics is more significant on $Nu(Re_L)^{-1/2}$ compared to $C_f(Re_L)^{1/2}$ effects. This can be credited to the fact that the variation of viscosity (with temperature) affects the momentum equation only through N , while its influence on the energy equation is mediated by both N and Pr , together with the derivative of Pr .

Furthermore, Fig. 2 illustrates that for changing fluid characteristics, the location of zero skin friction shifts upstream relative to unchanging fluid characteristics. Fig. 3 depicts the temperature and velocity profiles. The velocity distribution for varying the characteristics of the fluid vary from those of for fixed properties by approximately 4.55% at $\eta = 0.8$, while the temperature profile shows a difference of approximately 5.9% at $\eta = 0.8$.

Figure 4 shows that the coefficients for both heat transfer and skin friction rise when viscosity is constant compared to when it varies. The percentage disparity between the fixed and changing fluid characteristics, in the instance of heat transfer $Nu(Re_L)^{-1/2}$ coefficient is 0.31% at $m = 0.5$ and 17.5% for skin friction coefficient at $M = 0.5$. Therefore, skin friction is significantly influenced by MHD, whereas heat transfer shows minimal sensitivity to it.

Figure 5 presents the variations in velocity (F) and temperature (G) profiles for various values of the magnetic parameter M . It is observed that the magnetic field significantly influences both distributions. The applied transverse magnetic field induces a Lorentz force in the electrically conducting fluid, which modifies the momentum transport within the boundary layer. As M increases, noticeable changes occur in the velocity field, while the temperature profile shows enhancement throughout the boundary region. Consequently, the presence of the magnetic field alters the structure and thickness of the boundary layer.

To analyze the impact of the wall–fluid temperature difference (ΔT_w), which is responsible for variations in viscosity and Prandtl number on heat transfer coefficient and temperature curves

across the boundary layer are depicted as functions of ΔT_w (see Fig. 6). Considering $T_\infty = 28.7^\circ\text{C}$, the maximum ΔT_w is limited to 30°C to sustain the temperature within the permissible range ($< 40^\circ\text{C}$). The image shows that $Nu(Re_L)^{-1/2}$ declines as ΔT_w increases, while G rises with ΔT_w . Specifically, the heat transfer coefficient $Nu(Re_L)^{-1/2}$ reduces by 3.12% at $\Delta T_w = 20.0$ and the temperature profile increases by 5.92% at $\eta = 0.8$. A possible explanation for the variation in viscosity (μ) together with the Pr along the laminar boundary layer is the buoyancy forces, which create a temperature gradient among the fluid molecules and the wall surface.

The effect of the viscous dissipation parameter (Ec) on temperature and velocity profiles, considering non-constant fluid properties [$T_\infty = 28.7^\circ\text{C}$, $\Delta T_w = 10.0$], is revealed in Fig. 7. The results indicate that the velocity profile tends to increase, while the temperature profile decreases with a grow in the Eckert number (Ec). The impact of viscous dissipation is found to be more significant on the temperature profile compared to the velocity profile. While the viscous dissipation parameter (Ec) is explicitly present solely in the energy equation, its influence extends to the velocity profile due to the coupling between the energy–momentum equations, which arises from the temperature-dependent viscosity and Pr . Viscous dissipation causes heating of the fluid next to the wall, leading its temperature to exceed the wall temperature, even though the wall was initially hotter [$T_\infty = 28.7^\circ\text{C}$, $T_w = 38.7^\circ\text{C}$, $\Delta T_w = 10.0$]. Consequently, the cooler free stream is unable to effectively cool the heated wall because of the insulating effect of frictional heating. This behavior results in a lower heat transfer rate between the wall and the fluid. Furthermore, when $Ec \neq 0$, the temperature gradient becomes negative, indicating a reversal in the direction of heat transfer originating from the wall-to-fluid direction to fluid-to-wall. In the absence of viscous dissipation ($Ec = 0$), heat transfer occurs in the expected manner, with thermal energy diffusing from the wall into the surrounding fluid.

5 Conclusions

This study examines the steady laminar boundary layer flow of ethanol over an axisymmetric wedge by accounting for variable viscosity, viscous dissipation, magnetic field effects, and the Prandtl number.

The numerical results show that the applied magnetic field has a strong influence on the flow behavior, leading to an increase in velocity while simultaneously reducing the temperature field. As a result, both the momentum and thermal boundary layers become thinner under stronger magnetic effects.

The changes in viscosity and Prandtl number within the boundary layer are largely governed by the temperature difference between the wall and the ambient fluid ΔT_w . This temperature variation induces buoyancy forces near the surface, which in turn modify the transport characteristics of the flow. These effects remain consistent across the parameter ranges considered in the present computations.

Viscous dissipation is found to play a significant role in the thermal response of the system. An increase in the dissipation parameter enhances the velocity profile but suppresses the temperature distribution, which ultimately leads to a reduction in the surface heat transfer rate.

The present study is limited to steady, laminar flow assumptions. Future work may extend the present model to unsteady flow conditions, nanofluid suspensions, or non-Newtonian ethanol-based fluids to explore more complex and industrially relevant transport phenomena.

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