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Significance of Viscous Dissipation on Heat Transport in an Incompressible Viscous Fluid with Varying Properties: A Numerical Investigation

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ABSTRACT: This study investigates the behaviour of a viscous, electrically conductive, and incompressible fluid flow under the influence of magnetohydrodynamics (MHD) and viscous dissipation phenomena. This analysis encompasses the combined effects of variable thermal conductivity and non-uniform viscosity, taking into account the substantial implications these factors have on heat transfer within the fluid. As temperature varies, it is essential to consider that the fluid's viscosity and thermal conductivity will also change, significantly impacting flow characteristics. To model the governing equations of this complex system, a set of nonlinear ordinary differential equations, simplified through similarity transformations has been employed. The resulting similarity equations are then solved numerically using the MATLAB solver technique, allowing us to explore various flow parameters. The numerical calculations yield insights into temperature distributions, velocity profiles, Nusselt numbers, and the surface friction coefficient. These findings are crucial for applications in various fields, such as aerospace engineering, where understanding fluid dynamics around heated surfaces is vital. Additionally, this research can be applied to cooling systems in electronic devices, chemical processing industries, and even in bioengineering. These applications exemplify the importance of understanding such fluid behaviours in both theoretical and practical contexts.

Key Words: Heat transfer, MHD, variable thermal conductivity, viscous dissipation, variable viscosity

Contents

1. Introduction

Recently, there has been a notable increase in the study of the flow of incompressible fluids, specifically electrically conducting viscous fluids, in continuous vertical tubes. This investigation is essential because of its diverse applications in several sectors, such as combustion processes, depleted nuclear fuel management, ferrous waste treatment, preventative strategy research, and cooling systems for nuclear reactors. For instance, unconfined segments of material previously extruded from a die are let to cool by being dragged through a chilling bath and subsequently extended to the maximum extent feasible through various technical processes involving polymers. Under the context of heat allocation, the consequences of turbulent dissipation on transpiration flow across a sphere with temperature-sensitive conductivity have been investigated by Haqueet et al. [12]. They have noticed that for increasing amounts of the Eckert quantity, conductivity variance parameter, and the emission of heat dimension, the degree of heat inside the outermost region rises. Umavathi et al. [23] have investigated first-order chemical interactions and the coalesce influence of changing stiffness and heat flux on the compound convection movement of an opaque fluid in a vertical passageway and have come to the conclusion that the initial order compound reaction parameter, as well as the dimensionless stiffness parameter, the independent thermal conductivity component, the wall heating ratio, the Brinkman number, and other variables were consistent on a given concentration region. Attributes of double-diffusive transpiration in a permeable annulus in terms

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of the conveyance of heat and mass has been studied by Dutta and Kalita [9]. Implications of varying thickness and thermal insulation on the MHD motion of a micropolar fluid having a uniform heat flux over a porous material during unstable free convection has been examined by Parash and Hazarika [18]. They have summarized that there is a rise in temperature with the changed values of Eckert numbers. Using Casson EMHD to model heat transport, B. Dey et al. [7] examined how radiative and ohmic heating affect fluid motion. Their research shows that Eckert numbers increase thermal radiation and specific heat temperature profiles. The Casson parameter and local electric parameters decrease as they rise. The Eckert number affects heat transfer mechanisms differently. It has been discovered by Gbadeyan et al. [10] that when the intensity of varied thermal conductivity and thickness rise, the velocity upsurges while the ambient temperature and tiny particles volume fraction descent. Viscous fluid motion on a flattened surface having dynamic temperature and heat transfer has been analysed by Dey et al. [8] and established that temperature increases with Eckert number. Aqueous slip flow across an impermeable channel under hydromagnetic oscillations has been studied by Choudhury et al. [4]. Hydrodynamic abrasion, conductivity of heat, and slippage effects on magnetohydrodynamic micropolar flow have been pursued by Rahman et al [20] and have established that with a higher viscosity value, the amount of thickness of the thermal separation layer is considerably increased. Efficacy of varying viscosity and thermal conductance in view of similarity elucidation for substantial MHD Falkner Kan heat and mass transport flow over a propel in absorbent channel in view of thermal-diffusion and diffusion-thermo has been explored by Magahedet et al. [14]. In their study [6], Dey and Choudhury investigated the issue of a visco-elastic fluid moving in a horizontal channel while heat transfer was taking place.

In almost all the aforementioned experiments, either viscosity or thermal conductivity is changeable, or both, since it is commonly acknowledged that a fluid's viscosity, in particular, may vary significantly with variations in temperature. The decrease in stickiness inside the boundary layer, which demonstrates momentum as temperature increases, influences the transport phenomena and thus impacts the rate of heat transfer at the wall. The fluid's temperature-dependent viscosity must be considered when determining circulation and heat transfer rates. Also, there are several uses for viscous dissipation: In polymer manufacturing operations like polymer injection mouldings or the extrusion process with significant rates, considerable temperature spikes are mentioned a few, explained extensively by various authors [17] - [24]. Again, the effect of MHD on fluid flow has many applications. Goud [11] & Choudhury, et al. [5] have explained how an accelerating vertical porous plate has an influence on the thermostatically stratified MHD fluid flow. The radiative flow of Williamson nanofluid over a stretched sheet in the presence of a heat source, Arrhenius activation energy, and motile microorganisms was investigated by K. Malleswari et al. [15] in the context of magnetohydrodynamics (MHD). An investigation of the rotating magnetohydrodynamics (MHD) circulation and heat transfer of a generalised Maxwell fluid with dispersed order features was carried out by Y. Qiao et al. [19] across an infinite plate.

The present research concentrates on fluid properties that need elevated temperatures as a consequence of their nature. The major objective of this study was to examine the effects of varying fluid viscosity and electrical conductivity on magnetohydrodynamics, as well as viscous dissipation inside the boundary layer circulation and thermal transfer of viscous fluid flowing past a vertical wall. The fluid is presumably viscous, electrically conductive, and incompressible. Viscosity and thermal conductivity are considered factors of the neighborhood concentration. Investigations have been conducted to ascertain the influence of factors such as the Prandtl number, Eckert number, magnetic parameter, variable thermal conductivity, and fluid viscosity on flow behaviors and heat transfer, with evaluations performed numerically using the MATLAB solver bvp4c. Whenever the parameters for viscous dissipation, varying viscosity, and varying thermal conductivity are overlooked, the juxtaposition of the current investigation by Abiodun et al. [2] and Manjunatha, Gireesha [16] demonstrates a great compatibility. The problem addressed here has practical importance for cooling systems, food extraction, manufacturing, medical applications, and electronic devices. The subject is novel, and there are currently no relevant research in the literature.

2. Mathematical Formulations

Taking into account the amalgamated effect of changing viscosity and varying thermal conductivity on concentric heat exchange of flow of an impermeable indestructible viscous fluid past a flat plate together with viscous dissipation and magnetohydrodynamics (MHD). The x-axis is positioned vertically along the plates, where the flow is presumptively in the x-direction, and the y-axis is taken perpendicular to it which can be depicted by Figure 1, following Siddiqa and Hossain [22].

The continuity, momentum, and energy conservation equations for the flow with stable, laminar, and 2-dimensional boundary layers are expressed as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2.1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial y}\{\mu(T)\frac{\partial u}{\partial y}\} - \frac{\sigma B^2}{\rho}u + g\beta(T - T_\infty) \tag{2.2}$$

$$u\frac{\partial T}{\partial x} = v\frac{\partial T}{\partial y} = \frac{1}{\rho C_p}\frac{\partial}{\partial y}\{K(T)\frac{\partial T}{\partial y}\} + \frac{\mu(T)}{\rho C_p}(\frac{\partial u}{\partial y})^2 \tag{2.3}$$

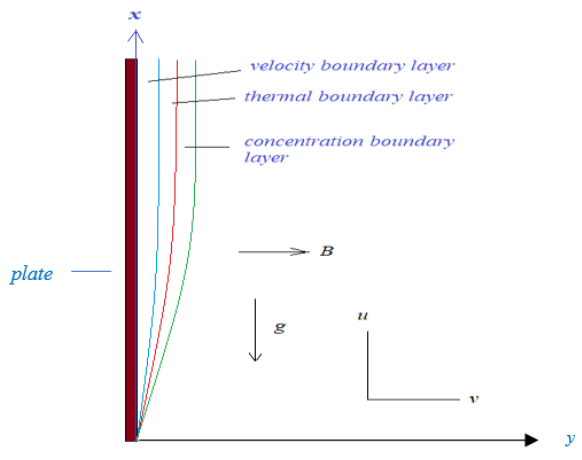

Figure 1: Flow Geometry

whereas the boundary circumstances are:

$$y = 0 : u = 0, v = 0, T = T_w$$

$$y \to \infty : u = U, T = T_\infty \tag{2.4}$$

here, T_w is the temperature of the plate, T_∞ is the temperature of free stream, and U is the stream velocity, respectively.

The similarity variables are introduced as follows:

$$\eta = \sqrt{\frac{u}{\nu_\infty x}}y, \Psi = \sqrt{U\nu_\infty x}f(n), \theta = \frac{T - T_\infty}{T_w - T_\infty} \tag{2.5}$$

Also, the temperature of the plate has been conjectured to vary along the plate in the following fashion:

$$T_w - T_\infty = Ax^m \tag{2.6}$$

where A and m are positive constants.

1. Viscosity variation model It is assumed that viscosity inversely varies with temperature and this is stated as:

$$\mu(T) = \frac{\mu_\infty}{1+\alpha_1(T-T_\infty)}, \tag{2.7}$$

Thus $T - T_\infty = Ax^m\theta$ which implies

$$\mu(T) = \frac{\mu_\infty}{1+\alpha_1 Ax^m\theta} \tag{2.8}$$

Let

$$\theta_\mu = \frac{1}{\alpha_1(T_w - T_\infty)} = \frac{1}{\alpha_1 Ax^m} \tag{2.9}$$

Therefore,

$$\mu(T) = \frac{\mu_\infty\theta_\mu}{\theta_\mu + \theta} \tag{2.10}$$

2. Thermal conductivity variation model The conductive property of gas increases as its temperature elevates, but it decreases for liquids. As a result, we postulate that thermal conductivity takes the following forms:

$$K(T) = \frac{K_\infty}{1+\alpha_2(T_w - T_\infty)} = \frac{K_\infty\theta_k}{\theta_k + \theta} \tag{2.11}$$

where $\theta_k = \frac{1}{\alpha_2(T_w - T_\infty)}$

With the initiation of similarity variables (6), along with the confined models (8), (10) and using the boundary conditions the modified equations are as follows:

$$(\frac{\theta_\mu}{\theta_\mu+\theta})f''' - \frac{\theta_\mu}{(\theta_\mu+\theta)^2}\theta' f'' + \frac{1}{2}ff" - Mf' + G_r\theta = 0 \tag{2.12}$$

$$\theta" - \frac{(\theta')^2}{\theta_k+\theta} + P_rE_c(\frac{\theta_\mu}{\theta_k})(\frac{\theta_k+\theta}{\theta_\mu+\theta})(f")^2 + P_r(\frac{\theta_k+\theta}{\theta_k})(\frac{\theta' f}{2} - m\theta f') = 0 \tag{2.13}$$

Modified boundary conditions are:

$$\eta = 0 : f = 0, f' = 0, \theta = 1$$
$$\eta \to \infty : f' \to 1, \theta \to 0 \tag{2.14}$$

3. Solution of the problem

The combined set of simultaneous equations embodied in Equations (12) and (13) subject to constraint (14) has been resolved numerically by employing MATLAB's boundary value problem-solving technique. Visual representations are used to show the data for velocity, temperature, total amount of solute, and particle accumulation. Skin friction, the Nusselt number, the Sherwood number, and the momentum of particle diffusion are all represented numerically in the table below. The fundamental of bvp4c approach may be summed up as follows:

1. By introducing a series of considerations, such as a_j, j = 1, 2,..., 5 the pair of connected and non-linear equations (12) and (13) can be structured to constitute an ensemble of differential equations of unitary order. The aforementioned set of mathematical equations is turned into a function in the framework of MATLAB.

2. In the context of $a_j's$, boundary criteria are now given leftover form. This is entered into a leftover function that is coded in MATLAB.

By using incremental steps, the algorithm called bvp4c corrects the mistake of order 10^{-6}.

4. Results and Discussion

Adequately presentable findings have been documented in the search for the influence of varying viscosity, varied thermal conductivity, and varied fluid characteristics on afloat channel flow. The numerical method used produces understandable results on the change of pertinent flow parameters. The narrative of the written appraisal is supported with vivid visual representations and exhaustive tables. For parameters having values, $M = 2, P_r = 2.4, G_r = 2, E = 0.001, m = 3, \alpha_1 = 5, \alpha_2 = 6$ solutions to those parameters are retrieved, unless specified differently. Figures 2-5 depict the velocity trajectory in reaction to changes in various important parameters. A visual rendering of the ramification of the magnetic constraint, M, on fluid motion is proposed in Figure 2. The contour layout indicates that the introduction of an oblique magnetic field reduces fluid movement. Hydromagnetic drift result in the Lorentz force, an antagonistic force that prevents fluid flow, when a transverse magnetic field is present. The amplification of the magnetic constraint causes the fluid's velocity to slow ceaselessly as a result.

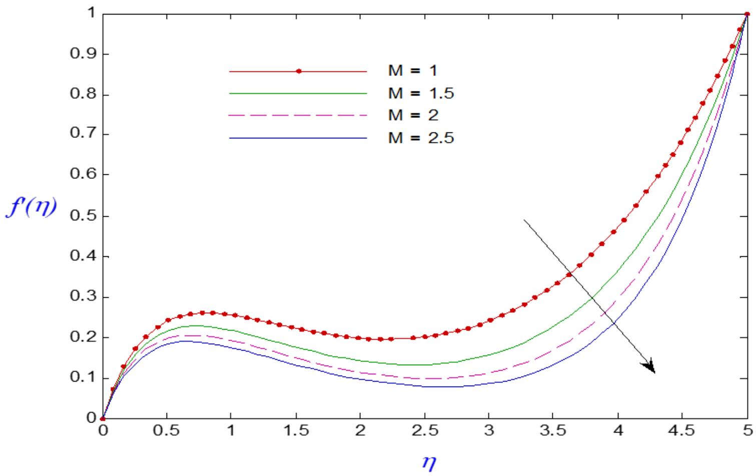

Figure 2: Velocity depiction for various values of M

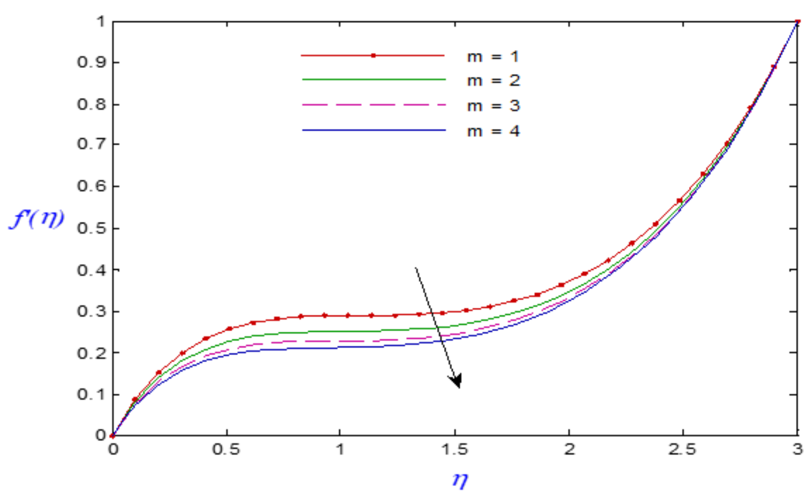

Figure 3: Velocity depiction for various values of m

The restricting effect of the changing stickiness parameter, α_1, on fluid transit is seen in figure 4. It is important to remember that for liquids, $\alpha_1 > 0$ and an increase in positive numbers signify a rise in fluid stickiness. Figure 4 illustrates how the fluid gets less agile as it grows stronger in viscosity.

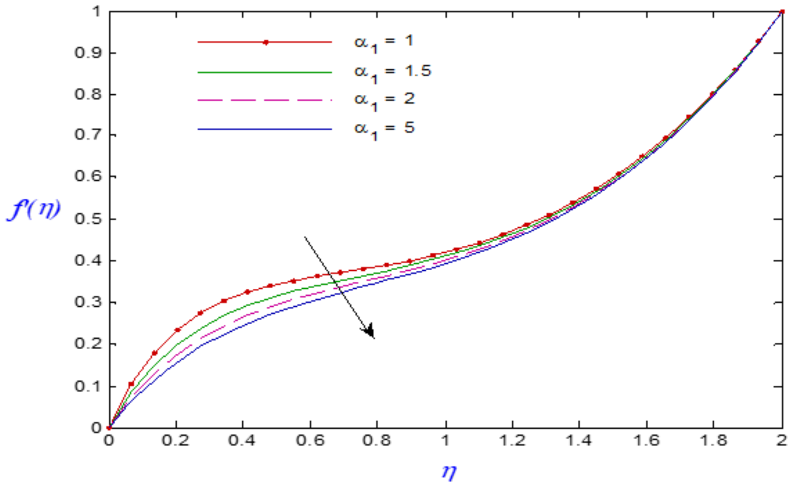

Figure 4: Velocity for fluctuation of α_1

The detrimental impact of the changing heat conductivity parameter α_2, on fluid movement is seen in figure 5. Fluid velocity increases as the value α_2 rises. A higher value of α_2, the thermal conductivity attribute implies a smaller gap between the reference temperatures, which causes more heat to be transferred between molecules. Aqueous fluidity increases as a result of this.

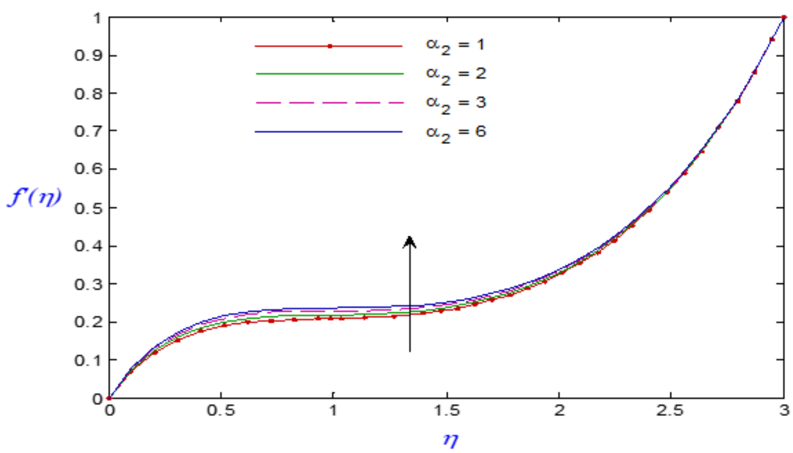

Figure 5: Velocity for fluctuation of α_2

Figures 6 to 8 exemplify the profile contours that characterize heat dispersion caused by variations in accompanying flow. Each visual representation reveals the effect of a given flow variant's hierarchical array of numerical values on the temperature of the fluid flow. Figure 6 shows the declining pattern with the uprising values of temperature variant parameter m.

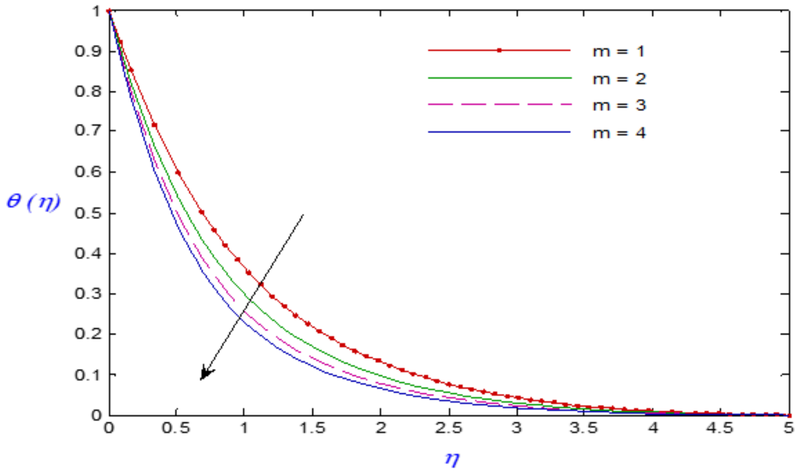

Figure 6: Temperature for m

Figure 7 illustrates the upward trend of the viscosity variation parameter α_1 on fluid temperature. The ambient temperature of the fluid escalates as α_1 is intensified. An increase in α_1 denotes a rise in fluid viscosity. An increase in viscosity drives a fluid's thickening up, which increases friction between fluid layers and generates additional heat.

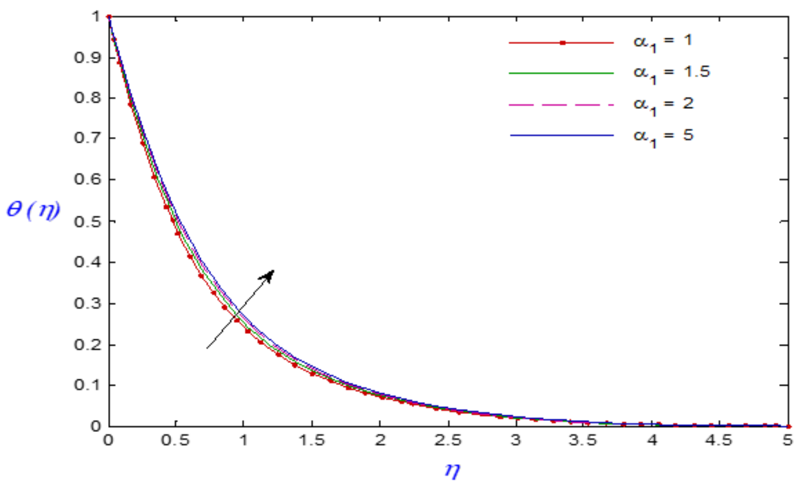

Figure 7: Temperature for α_1

Figure 8 emphasizes the effect of the thermal conductance parameter α_2 on the flow's distribution of heat. The ambient temperature of the fluid in the passageway rises when the value of α_2 increases. Increased fluid heat resistance is correlated with bolstering ($\alpha_2 > 0$). The pace at which combustion disperses increases in direct proportion to the fluid's thermal efficiency. As a result, the heat generated from the opposite side of the wall dissipates into the fluid more quickly, raising the ambient temperature of the fluid.

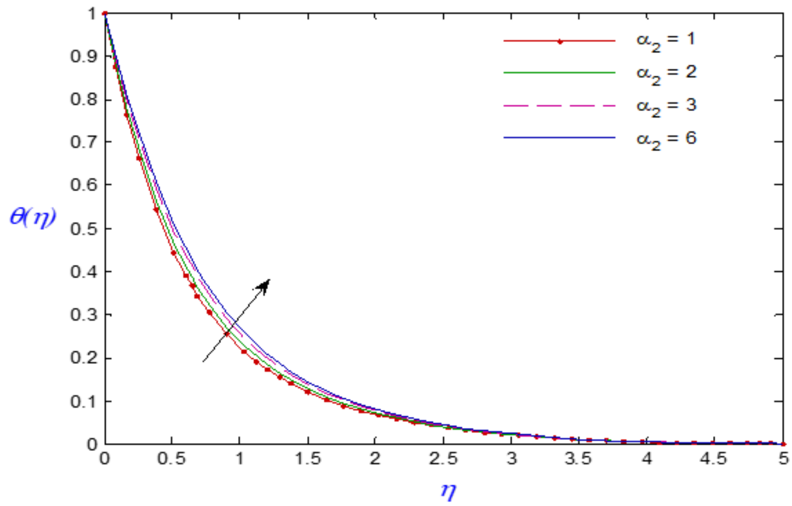

Figure 8: Temperature for α_2

Table 1 displays the outermost layer skin friction amounts in numeral format. It is evident that increasing the dissipation of viscosity tends to cause each threshold surface's friction between them to escalate. Additionally, the increase in thermal conductivity adds to a reduction in skin friction, which is because enhancing thermal resistance causes velocity to rise, which in turn results in a reduction in skin friction among the two walls. The chart also demonstrates that skin friction across both walls reduces with increasing viscosity and that skin friction is larger when the working fluid is air than when it is mercury.

Table 1: Approximated numerical appraisal of skin friction

M	S_f	m	S_f	α_1	S_f	α_2	S_f
1	0.94147	1	0.96277	0.5	1.6773	1	0.78493
1.5	0.88094	2	0.89594	1	1.3158	2	0.80806
2	0.83635	3	0.8522	2	1.0999	3	0.83635
2.5	0.80022	4	0.81988	5	0.95209	6	0.85323

The rates of heat transmission on the two boundary surfaces are shown numerically in Table 2. The efficiency of heat transmission on the heated surface decreases as viscosity increases and viscous dissipation takes place, whereas the cool plate shows the opposite pattern. Physically predicted due to the ambient temperature of the fluid drops at the part next to the hot plate during rising at the division next to the cooler plate as the viscosity elevates.

Table 2: Approximated numerical appraisal of rate of heat transfer

M	N_u	m	N_u	α_1	N_u	α_2	N_u
1	-1.3434	1	-0.9457	0.5	-1.4595	1	-1.5055
1.5	-1.2807	2	-1.1402	1	-1.3926	2	-1.3784
2	-1.233	3	-1.2808	2	-1.3451	3	-1.233
2.5	-1.1933	4	-1.3931	5	-1.3086	6	-1.1513

5. Conclusion

The appraisal of an incompressible fluid with irregular viscosity and thermal conductivity passing a flat plate is executed. The warmth of the plate varies along its length. The explications of the set of flow regulating analogy operated via a boundary value problem-solver of MATLAB, embellish the adherent extrapolations:

1. The velocity profile dwindles as there is a surge in magnetic parameter M, viscosity parameter α_1 and plate warmth parameter m. However, efflux in thermal conductivity parameter α_2 boosts fluid velocity.

2. Plate surface friction exhibits diminution owing to upsurge in magnetic effect, plate temperature and viscosity. The result is antithetical for thermal conductivity.

3. The temperature profile inflates with respective upswing in viscosity and thermal conductivity, but dwindles as the plate temperature parameter grows.

4. Hike in plate temperature parameter subdues the rate of heat transmission. However, respective enhancement in magnetic parameter, viscosity and thermal conductivity inflates the rate of heat transmission.

Nomenclature

B	magnetic field intensity
G_r	thermal Grashof number
g	acceleration due to gravity
M	magnetic parameter
S_f	Skin friction
T	fluid temperature
T_w	temperature at the plate
T_∞	free stream temperature
u, v	fluid velocity, m/s
m	plate warmth parameter
U	free stream-velocity, m/s
x, y	coordinate axes
α_1	viscosity parameter
α_2	thermal conductivity parameter
η	non-dimensional ordinate
θ	dimensionless temperature
k(T)	variable thermal conductivity, W/mK
k_∞	ambient thermal conductivity, W/mK
$\mu(T)$	variable viscosity, kg/ms
μ_∞	ambient viscosity, kg/ms
ρ	fluid density, kg/m^3
σ	electric conductivity, m/Ω
N_u	Nusselt number
P_r	Prandtl number
E_c	Eckert number
β	Volumetric expansion coefficient

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