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INVESTIGATION OF THE CONSEQUENCES OF ENERGY AND MASS TRANSFER ON THE CIRCULATION THROUGH A PARABOLIC STARTED INCLINED PLATE WITH FIRST-ORDER CHEMICAL REACTION AND UNIFORM THERMAL FLUX

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Abstract

The intention of this case is to investigate the energy and mass transfer effects on viscous, incompressible, and transient motion past an inclined plate started with a parabolic motion under uniform heat flux in the existence of a homogeneous initial-order chemical response. An effort is made to explain the characteristics of the inclined angle of the plate and chemical process parameters on the hydrodynamic

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flow field. Several dimensionless parameters are employed to reduce into dimensionless boundary layer equations. The resulting partial differential equations are tackled analytically utilizing the Laplace transform approach, and the required expressions for warmth, concentration, and flow tempo are obtained. The consequences of warmth, concentration, and flow tempo are studied graphically for various flow parameters like Prandtl number, chemical reaction parameter, time '*t*', thermal and mass Grashof number, angle of inclination, and Schmidt number. It is found that a rise in chemical reaction parameter or inclination angle causes the flow velocity to decrease rapidly whereas an increase in mass Grashof number or time causes flow velocity to increase.

Nomenclature

C - Indeterminate concentration

G_r - Thermal Grashof number

C' - Fluid content close to the plate

g - Velocity brought caused by gravity

C'_∞ - Freestream fluid concentration

C_p - Particular heat capacity under steady-state conditions

D - Coefficient of mass diffusion

G_c - Mass Grashof number

erfc - Complementary error function

exp - Exponential function

ν - Coefficient of kinematic viscosity

ρ - Density of the fluid

K_1 - Chemical reaction variable

y' - Axis normal to the plate

η - Axial similarity variable

K	-	Indeterminate chemical reaction variable
P_r	-	Prandtl number
q	-	Heat flux per unit area
μ	-	Coefficient of dynamic viscosity
S_c	-	Schmidt number
X	-	Indeterminate axis running the length of the plate
T	-	Indeterminate temperature
x'	-	Axis along the plate
k	-	Thermal conductivity
T'	-	Warmth of the fluid close to the plate
β^*	-	Coefficient of volumetric expansion with concentration
T'_∞	-	Freestream fluid temperature
u	-	Velocity of the fluid in x'-direction
U	-	Dimensionless velocity
u_0	-	Initial velocity of the fluid in x'-direction
Y	-	Dimensionless plane perpendicular to the dish
β	-	Coefficient of heat expansion in volume

1. Introduction

First-order chemical reactions are those in which the reaction rate over time is proportional to the amount of fluid substance. Speaking generally, most of the chemical reactions are first-order in nature. These first-order chemical reactions coupled with mass and energy transfer phenomena play an essential element in designing heat exchangers which are widely used in refrigeration, electronic components cooling systems, power plants, and chemical plants. A combined examination of mass and heat transfer along with chemical reactions is widely employed in food processing industries.

The analysis of electrically conductive fluid flows through externally applied magnetic fields is known as magnetohydrodynamics, and it was conducted by Davidson [1]. Soundalgekar [2] detailed examination of how mass transfer affects the Stokes problems for a boundless upward plate while accounting for free-convection currents has been provided. It has been discovered that a mass transfer causes the velocity to increase. However, a decrease in velocity occurs as the $S_c\,(< 1)$ grows. When there is a foreign mass and S_c is less than 1, the skin friction rises; however, when S_c is equal to 1, it reduces. Das et al. [3] explained the nature of transitory free-convective circulation when periodic plate temperature with rate imposed on the mean plate temperature. Various plate conditions and transient laminar-free convection flow via a boundless upward plate have been researched by numerous researchers. Transient free convection flow occurs in many engineering applications because it functions as a cooling mechanism. On the other hand, adding fluctuating heat on top of the mean plate temperature improves free-convection flow. The consequences of mass transfer on flow past an infinitely long straight plate that was initiated impulsively under first-order chemical reactions and uniform heat flux were also examined by Agrawal et al. [4]. In the midst of a slanted magnetic field parameter, chemical reaction, and heat generation, a precise study of the radiative hydromagnetic flow behavior across a tilted parabolic plate via a permeable media with changing species concentration and fluid temperature was discovered by Endalew and Sarkar [5].

Considering the existence of heat rays, a heat source, and a chemical process, Agarwalla and Ahmed [6] examined the Soret phenomenon and the consequences of the direction of inclination on circulation and transport characteristics. An endless inclined plate immersed in a saturated porous medium with changing plate acceleration, heat, and mass diffusion, was the object of their analysis, which involved analyzing a precise resolution of unstable magnetohydrodynamics free convective mass transfer movement. Apelblat [7] examined the mass transfer in conjunction with a first-order irreversible chemical process in plug and Couette flows with a shifting user interface and the entire flow of boundaries. Additionally, asymptotic expressions and analytical solutions for varied chemical reactions were suggested. Additionally, certain extensions are provided for mass transport in non-Newtonian fluids or porous surfaces. Das et al. [8] assessed the consequences of natural convection on heat transport over an isothermal slanted panel. In the midst of species abundance, steady movement of warmth at the surface, and initial-order chemical process, Das et al. [9] obtained a precise response to the flow caused by the impulsive motion of an endless straight sheet in its plane applying the Laplace-transform technique. Whenever the heat flow is steady between the liquid as well as the sheet, Singh and Singh [10] described how the mass transfer effect affects the free-convection flow of an incompressible viscous liquid past an endless horizontal panel that is evenly accelerated. A theoretical approach was used to generate the formulas for the skin friction and the velocity field. Fujii and Imura [11] stated that the convective warmth deportation coefficient of a prone warming sheets exposed to natural convection is equal to the power of the product of the cosine portion of the prone slope 'h' from the regular plane and the gravitational stimulation 'g'.

Yu and Lin [12] studied the consequences of mass transfer and heat on a magnetohydrodynamic flow across a prone porous sheet in the existence of a chemical process. Several unstable free convection flows close to a vertical sheet were looked at by Ganesan and Palani [13] at the boundary plate under various temperature circumstances. Bhuvaneswari et al. [14] examined how energy and mass transfer factors affect a magnetohydrodynamic flow across an inclined porous sheet when a chemical process exists. In an energy source and a chemical reaction, Nayak [15] examined the consequences of mass and energy transfer in a boundary layer moving over a porous medium of a magnetically conductive viscoelastic liquid exposed to a cross-sectional magnetic field. Manivannan et al. [16] investigated the unstable motion of a viscous incompressible flow across an endless isothermal straight oscillation sheet in the presence of thermal radiation and a uniform first-order chemical response. Muthucumaraswamy and Velmurugan [17] studied a precise answer of an irregular stream past a parabolic beginning movement of an endless straight sheet with parameter warmth and mass diffusion. They also discovered that the temperature of the sheet and the concentration level close to the sheet grow in a linear over time 't'. Visalakshi and Vasanthabhavam [18] examined the effects of internal friction on the unstable magnetohydrodynamics free convective stream through a parabolic beginning act of the endless horizontal sheet with variable heat and mass diffusion. As an outcome of a diagonally working magnetic field, Selvaraj et al. [19] specifically examined the rotation impact of an unstable laminar flow over an impermeable and electrically driven fluid across a homogeneous sped-up unbounded equilibrium opposed sheet.

In the absence of magnetohydrodynamics, Dilip Jose and Selvaraj [20] investigated a diagnostic theory of spinning consequences on unreliable parabolic movement past of an indestructible and electrically leading liquid past a frequently sped-up tremendous isothermal opposed sheet in the form of an initial-order chemical response. Pattnaik et al. [21] addressed the impacts of the magnetic field, the permeability of the porous media, and the material properties. Sandhya et al. [22] discussed the Soret implications and the impact of a degree of prone on the flow field in the context of the chemical process, and energy. Additionally, the effects of heat and mass transfer on the movement of magnetohydrodynamics across a prone porous sheet in a chemical reaction were investigated. The uneven MHD flow across an inclined sheet surrounded by a penetrable mechanism with a chemical reaction and a Soret-aligned magnetic field was evaluated by Raghunath and Venkateswaraju [23].

However, heat and mass transfer effects on flow past an inclined plate accelerated parabolically under uniform heat flux along with first-order chemical reaction are not investigated in the literature. Hence it is suggested to investigate the heat and mass transfer phenomena on flow past a parabolically accelerated inclined plate under consistent heat flow in the absence of a chemical process. The governing non-dimensional boundary layer calculations are tackled by the Laplace transform approach, and the corresponding analytical answers are achieved concerning exponential and error functions. Numerical computations of temperature, concentration, and flow velocity are visualized through graphs implemented by MATLAB software.

2. A Mathematical Investigation

Consider the transient flow of an incompressible fluid of a viscous nature past an inclined plate of infinite length under uniform heat flux in the existence of a first-order homogeneous chemical process. The straight orientation is reserved as x' axis and the upright orientation is taken as the y' axis. The infinite plate is inclined at an angle α to x' axis. Originally, both the fluid and the plate are presumed to be at the equivalent temperature (T'_∞), and concentration (C'_∞) that of freestream at all points and kept constant. At the time $t' > 0$, the plate begins for movement with a velocity of parabolic profile $u = u_0 t'^2$ against gravity. The plate temperature is amplified under uniform heat flux to T'_w and the concentration in the vicinity of the surface is elevated to C'_w. Based on the aforementioned factors, the governing boundary layer formulas are as follows:

Momentum equation

$$\frac{\partial u}{\partial t'} = g\beta(T' - T'_\infty)\cos\alpha + g\beta^*(C' - C'_\infty)\cos\alpha + \nu\frac{\partial^2 u}{\partial y'^2}. \tag{2.1}$$

Energy equation

$$\rho C_p \frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2}. \tag{2.2}$$

Species equation

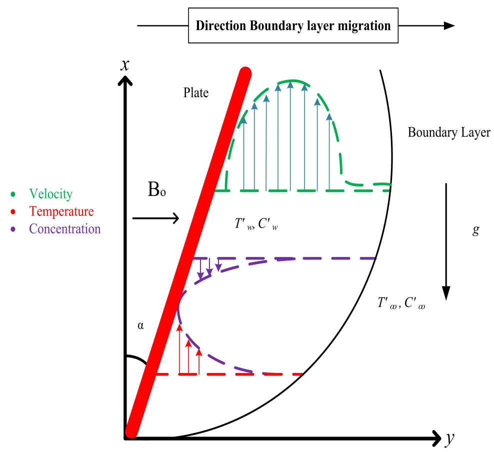
$$\frac{\partial c'}{\partial t'} = D\frac{\partial^2 c'}{\partial y'^2} - K_1(C' - C'_\infty). \tag{2.3}$$

Along with boundary conditions,

$$t' \leq 0, \quad u = 0, \quad T' = T'_\infty, \quad C' = C'_\infty, \quad \forall y' \leq 0, \tag{2.4}$$

$$t' > 0, \quad u = u_0 t'^2, \quad \frac{\partial T'}{\partial y'} = \frac{-q}{k}, \quad C' = C'_w, \text{ at } y' = 0, \tag{2.5}$$

$$t' > 0, \quad u \to 0, \quad T' \to T'_\infty, \quad C' \to C'_\infty, \text{ as } y' \to \infty. \tag{2.6}$$



The non-dimensional quantities listed below are now presented:

$$U = u\left(\frac{u_0}{\nu^2}\right)^{1/3}, \quad t = \left(\frac{u_0^2}{\nu}\right)^{1/3} t', \quad Y = y'\left(\frac{u_0}{\nu^2}\right)^{1/3}, \quad T = \frac{T' - T'_\infty}{\frac{q}{k}\left(\frac{\nu}{u_0}\right)^{\frac{1}{3}}},$$

$$G_r = \frac{\nu^{1/3} g\beta q}{k u_0^{2/3}}, \quad G_c = \frac{g\beta^*(C'_w - C'_\infty)}{(\nu u_0)^{1/3}}, \quad P_r = \frac{\mu c_P}{k}, \quad S_c = \frac{\nu}{D}, \quad K = \frac{K_1 \nu}{u_0^2}. \tag{2.7}$$

Using the above dimensionless quantities (2.7), equations (2.1)-(2.3) are reduced to

$$\frac{\partial U}{\partial t} = G_r T \cos\alpha + G_c C \cos\alpha + \frac{\partial^2 U}{\partial Y^2}, \tag{2.8}$$

$$\frac{\partial T}{\partial t} = \frac{1}{P_r} \frac{\partial^2 T}{\partial Y^2}, \tag{2.9}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c} \frac{\partial^2 C}{\partial Y^2} - KC. \tag{2.10}$$

Additionally, the boundary conditions (2.4)-(2.6) are simplified to

$$U = 0, \quad T = 0, \quad C = 0, \quad \forall Y,\, t \le 0, \tag{2.11}$$

$$U = t^2, \quad \frac{\partial T}{\partial Y} = -1, \quad C = 1 \text{ at } Y = 0, \tag{2.12}$$

$$U \to 0, \quad T \to 0, \quad C \to 0 \text{ as } Y \to \infty. \tag{2.13}$$

3. A Mathematical Investigation

The dimensionless governing equations (2.8) to (2.10), subject to the corresponding initial and boundary conditions (2.11) to (2.13), are tackled by using the Laplace transformation technique and error functions discussed by Hetnarski [24].

The analytical solutions for the hydrodynamic flow field in terms of flow concentration, temperature, and velocity are obtained as follows:

$$T = 2\sqrt{t}\left[\frac{\exp(-\eta^2 P_r)}{\sqrt{\pi}\sqrt{P_r}} - \eta\, erfc(\eta\sqrt{P_r})\right],$$

$$C = \frac{1}{2}[\exp(-2\eta\sqrt{S_c K t})\, erfc(\eta\sqrt{S_c} - \sqrt{Kt})$$
$$+ \exp(2\eta\sqrt{S_c K t})\, erfc(\eta\sqrt{S_c} + \sqrt{Kt})],$$

$$U = \frac{t^2}{3}\left[(3 + 12\eta^2 + 4\eta^4)\, erfc(\eta) - \frac{\eta}{\sqrt{\pi}}(10 + 4\eta^2)\exp(-\eta^2)\right]$$
$$+ \frac{G_r \cos\alpha t^{3/2}}{3(1 - P_r)\sqrt{P_r}}\left[\frac{4}{\sqrt{\pi}}(1 + \eta^2 P_r)\exp(-\eta^2 P_r) - \frac{4}{\sqrt{\pi}}(1 + \eta^2)\exp(-\eta^2)\right.$$
$$\left. - \eta\sqrt{P_r}(6 + 4\eta^2 P_r)\, erfc(\eta\sqrt{P_r}) + \eta(6 + 4\eta^2)\, erfc(\eta)\right]$$
$$+ \frac{G_c \cos\alpha e^{at}}{2a(1 - S_c)}[\exp(-2\eta\sqrt{S_c(a + K)t})\, erfc(\eta\sqrt{S_c} - \sqrt{(a + K)t})$$

$$+\exp(2\eta\sqrt{S_c(a+K)t})\,erfc(\eta\sqrt{S_c}+\sqrt{(a+K)t})]$$

$$+\frac{G_c\cos\alpha}{1-S_c}[\exp(-2\eta\sqrt{at})\,erfc(\eta-\sqrt{at})-\exp(2\eta\sqrt{at})\,erfc(\eta+\sqrt{at})]$$

$$+\frac{G_c\cos\alpha}{a(1-S_c)}\Big[erfc(\eta)-\frac{1}{2}[\exp(-2\eta\sqrt{S_cKt})\,erfc(\eta\sqrt{S_c}-\sqrt{Kt})$$

$$+\exp(2\eta\sqrt{S_cKt})\,erfc(\eta\sqrt{S_c}+\sqrt{Kt})]\Big],$$

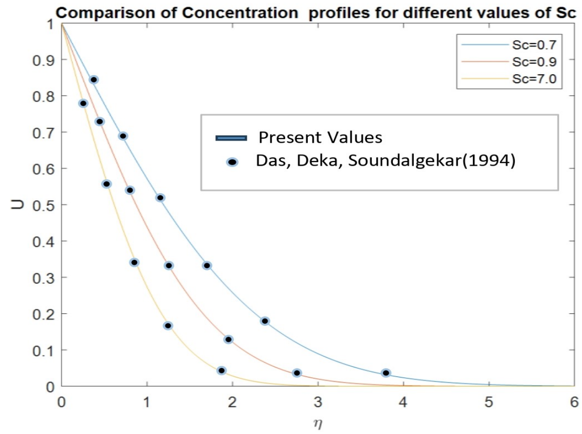
where $\eta=\frac{y}{2\sqrt{t}}$ and $a=\frac{KS_c}{1-S_c}$.

4. Results and Discussions

Numerical computations are executed using MATLAB software for several flow parameters to experience the physical insight of the problem. The foundations of Prandtl number 'P_r' are taken as 7 (water) and 0.71 (air). The principles of Schmidt number 'S_c' are interpreted as 0.16 (hydrogen), 0.3 (helium), and 0.6 (water vapor). The basic concepts of the inclination angle are chosen as $\frac{\pi}{6}$, $\frac{\pi}{4}$, and $\frac{\pi}{3}$.

Comparison of numerical results

In order to validate the present results, the numerical values are compared with the available theoretical solutions from the literature (Das et al. [9]). The trend shows that the present results are found to coincide with the previous studies. The comparison results are presented in the following graph for the concentration field with phase angle $\alpha = 0$, $\beta = 0$, $G_r = 5$, $G_c = 5$, $t = 0.2$, $S_c = 0.7, 0.9, 7.0$.



Effect on temperature profiles

Figure 1 shows the variation of temperature (T) for air $(P_r = 0.71)$ concerning axial distance (η) for different times. From this plot, it is observed that temperature profiles are increased when time is increased.

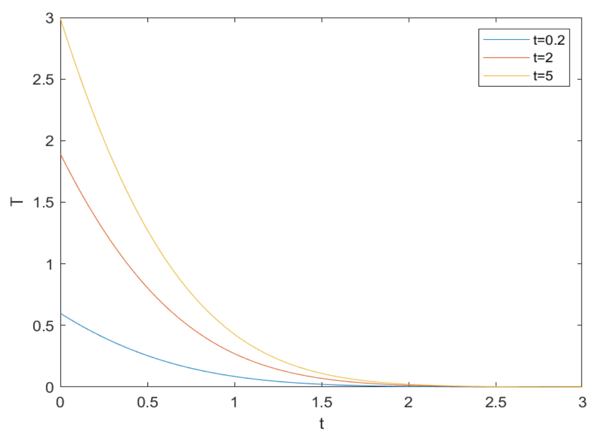


Figure 1. Temperature (T) vs time (t).

Figure 2 shows the variation of temperature (T) concerning axial distance (η) at time $t = 0.2$ for $P_r = 0.71$ (air) and $P_r = 7$ (water). We can observe that temperature rises when there is a fall in Prandtl number (P_r). This is because thermal conductivity (k) and Prandtl number (P_r) are inversely proportional to each other.

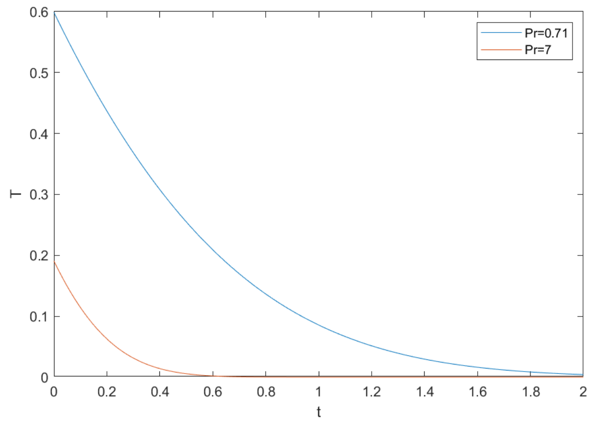


Figure 2. Temperature (T) vs Prandtl number (P_r).

Effect on concentration profiles

Figure 3 explains the variation of concentration profiles (C) for air with respect to axial distance (η) for different chemical reaction parameters (K) at time $t = 0.2$. It is detectable that concentration declines asymptotically with an appreciable rise in chemical reaction parameter (K).

Figure 4 explains the variation of concentration profiles (C) for air with respect to axial distance (η) for different Schmidt numbers (S_c) at time $t = 0.2$. Concentration falls rapidly if there is an upturn in Schmidt number this is because the rise in Schmidt number causes the diffusivity (D) to fall gradually which in turn reduces the concentration of the fluid.

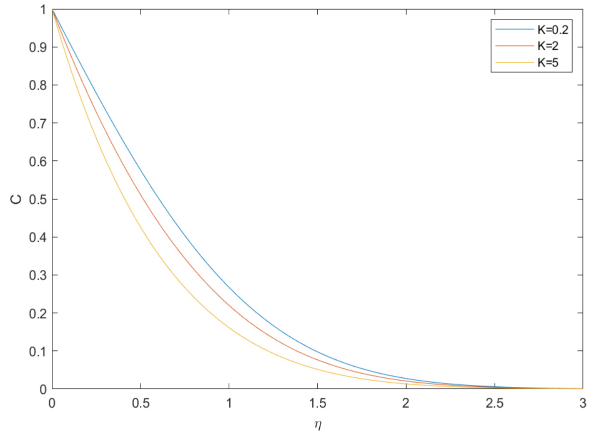


Figure 3. Concentration (C) vs chemical reaction parameter (K).

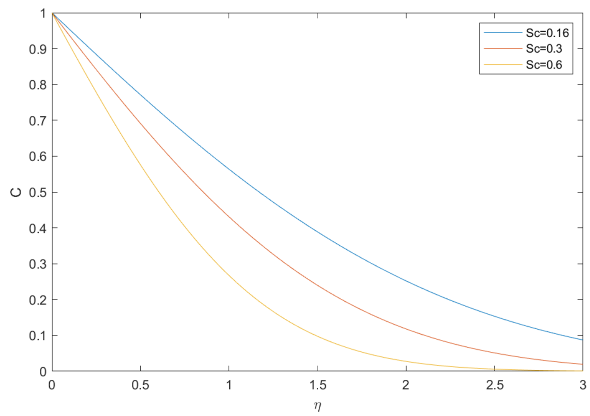


Figure 4. Concentration (C) vs Schmidt number (S_c).

Effect on velocity profiles

The impact of flow factors like the chemical process (K), angle of inclination (α), mass Grashof number (G_c), time (t), and Schmidt number on velocity profiles are investigated to get a comprehensible description of the flow field.

Figure 5 exposes the consequences of a chemical process (K) on flow velocity via $P_r = 0.71$, $t = 0.2$, $G_c = 5$, $S_c = 0.6$, $G_r = 5$, and the plate is inclined at an angle of 60° to X axis. It is seen from the figure that velocity declines with a slight rise in the chemical reaction parameter.

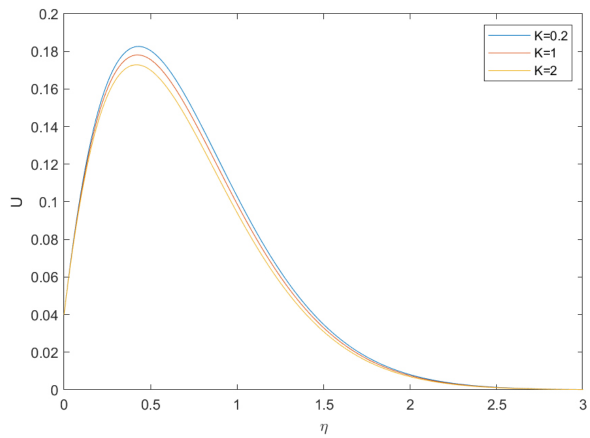


Figure 5. Velocity (U) vs chemical reaction parameter (K).

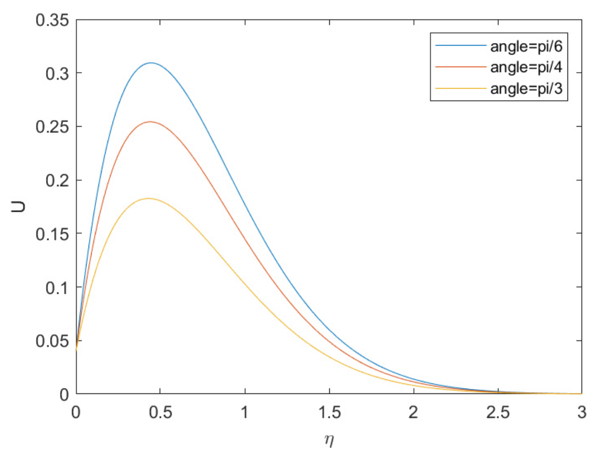


Figure 6. Velocity (U) vs angle of inclination (α).

Figure 6 elucidates the variation of velocity due to angle of inclination (α) at time $t = 0.2$ and $K = 0.2$. From this plot, it is transparent that a significant growth in the angle of inclination causes velocity to fall drastically. Maximum velocity is achieved close to the plate and gradually starts diminishing while moving away from the plate.

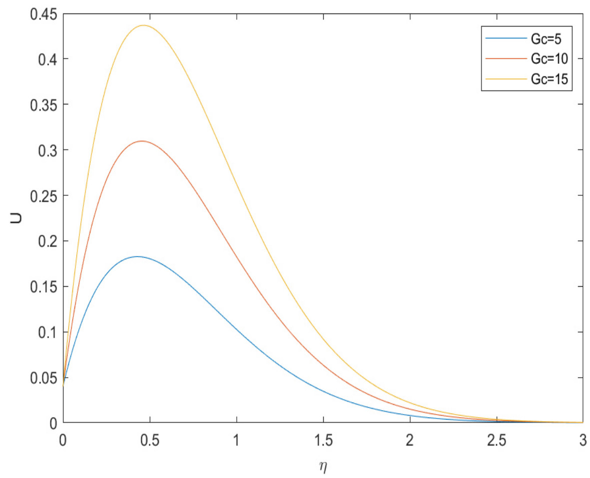


Figure 7. Velocity (U) vs mass Grashof number (G_c).

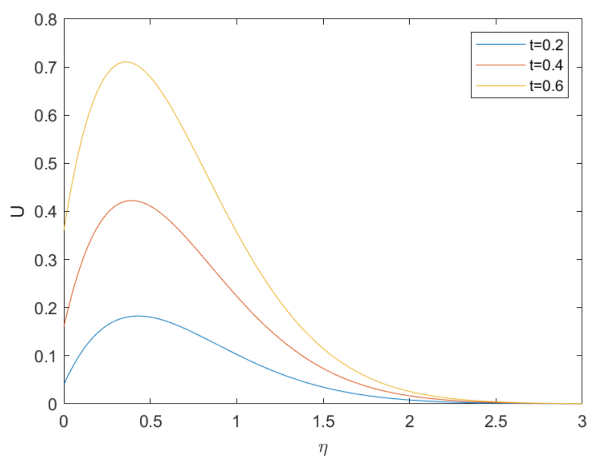


Figure 8. Velocity (U) vs time (t).

Figure 7 describes the effect of mass Grashof number (G_c) on flow velocity for air along $P_r = 0.71$, $\alpha = 60^\circ$, $S_c = 0.6$, $K = 0.2$, $t = 0.2$ and $G_r = 5$. Figure 8 describes the effect of time on flow velocity with $P_r = 0.71$, $K = 0.2$, $S_c = 0.6$, $G_r = 5$, $G_c = 5$, and $\alpha = 60^\circ$. From Figures 7 and 8, it is clear that a slight growth in the mass Grashof number and time significantly expands the velocity but the effect of time over velocity is superior to mass Grashof number. Figure 9 illustrates the consequence of Schmidt number (S_c) on flow velocity with $P_r = 0.71$, $t = 0.2$, $K = 0.2$, $G_r = 5$, $G_c = 5$, and $\alpha = 60^{\circ}$. It is found that raise in Schmidt number causes velocity to decline notably.

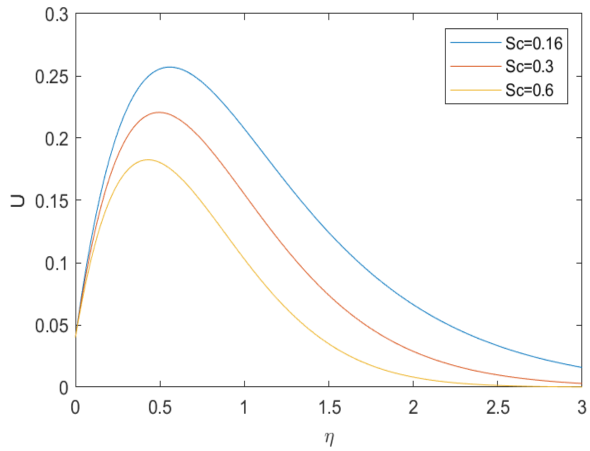


Figure 9. Velocity (U) vs Schmidt number (S_c).

5. Conclusion

The analytical explanation of transient flow past an inclined plate started parabolically under constant heat flux in the presence of an initial-order chemical process factor has been reviewed. The boundary layer calculations are non-dimensionalized by various non-dimensional parameters and tackled using the Laplace methodology. The consequences of factors like chemical process factor, Schmidt number, mass Grashof number, angle of inclination, and time are investigated graphically and findings are made as follows:

- The temperature of the fluid close to the plate rises with a significant growth in time whereas declines with increasing Prandtl number.

- Concentration near the plate declines with an ascent in chemical process parameters as well as Schmidt number.

- Velocity diminishes with a significant rise in chemical reaction parameter and Schmidt number but the role of Schmidt number is more dominant than chemical reaction parameter over flow velocity profiles.

- Velocity rises with remarkable growth in time (t) and mass Grashof number. It is noticed that the effect of time over velocity profiles is more superior than mass Grashof number.

- Extension in angle of inclination causes velocity to decrease notably.

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