

NON-LINEAR RADIATIVE FLOW OF NANOFUID PAST A MOVING/STATIONARY RIGA PLATE

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ABSTRACT

The effect of non-linear thermal radiation on nanofluid flow over a riga plate is studied. Under some conditions, our problem reduces to the Blasius problem and Sakiadis problem. Similarity transformation is used to convert the governing steady Navier-Stokes equations into a system of coupled nonlinear differential equations, which are then solved numerically via Runge-Kutta-Fehlberg 45 order method along with a shooting method. Influence of parameters involved on velocity, temperature and concentration profiles is discussed with the help of graphical aid. Numerical results have been presented on the skin-friction coefficients, local Nusselt number and Sherwood number. It is found that in skin friction values of Blasius flow is higher than skin friction values of Sakiadis flow.

Keywords: Nanofluid, Blasius/Sakiadis problem, nonlinear thermal radiation, Riga plate, numerical solution.

1. INTRODUCTION

Incompressible two dimensional fluid flows over a stretching surface has a vital behavior on several technological applications in the field of metallurgy, chemical engineering and various manufacturing processes such as stretching of plastic films, metal spinning, metal extrusion, artificial fibers, glass blowing, spinning of fibers and continuous casting. In view of the above applications Blasius (1908) was the first who proposed the boundary layer flow on a flat plate. Sakiadis (1961) extended the work of Blasius (1908) and studied the quiescent fluid flow past a moving plate. Afzal et al. (1993) analyzed the combined study of Blasius problem and Sakiadis problem and converted into a single set of equations by introducing composite velocity. Batailler (2008) extended the work of Afzal et al. (1993) by studied the effects of radiation in presence of convective boundary condition. Later on the effect of thermal radiation on two dimensional flows past a moving plate with convective condition was investigated by Ishak et al. (2011). Mukhopadhyay et al. (2011) obtained the dual solution for radiative flow of a porous moving plate. Ramesh et al. (2015; 2016) examined the viscous flow past an inclined stationary/moving flat plate in the presence of convective condition. Further they extended the work of Ishak et al. (2011) by considering Williamson fluid.

Base fluids such as water, engine oil and ethylene glycol contain low thermal conductivity and metals have thermal conductivities up to three times superior than base fluids. Addition of nano sized metallic particles in the base fluids significantly increases the thermo physical characteristics of the base fluids. Therefore nanofluids are new invention of conventional fluids. Choi (1995) was the person introduced the term nanofluid and experimentally shown that the inclusion of nanometer sized particles in the base liquids it enhances the thermophysical characteristics of the base liquids. Buongiorno (2006) examined the behavior of thermophoresis and Brownian motion and developed a mathematical model for nanofluids. Khan and Pop (2010) was the first persons introduce the concept of nanofluid in boundary layer theory. Bachok et al (2012) extended work of Khan and Pop (2010) to Blasius and Sakiadis problems. Kandasamy et al. (2013) incorporate the radiation effect on nanofluids and obtained both exact and numerical solution. Ramesh and Gireesha (2014) examined the heat

source/sink effects on Maxwell nanofluid over a stretching sheet in the presence of convective condition. Some of the recent studies in this direction can be seen Shehzad et al. (2014); Prasannakumara et al. (2016); Ul Haq et al. (2015); Sheikholeslami (2015); Das et al. (2014); Ramesh and Gireesha (2013); Hayat et al. (2015); Rashidi et al. (2014), Pantokratoras and Fang (2013); Turkyilmazoglu and Pop (2013) and Makinde (2005) and references there in. Thermal radiation has potential role in manufacturing design of nuclear power plants and various engineering processes. Numerous researchers have paid their attention to address the mechanism of thermal radiation. Hayat et al. (2016) analyzed the impact of nonlinear radiative flow over convectively heated cylinder. Makinde and Animasaun (2016) studied the nonlinear thermal radiation effect on bioconvection nanofluid with quartic reaction. A comprehensive literature on nonlinear thermal radiation can be found in the references Hayat et al. (2016), and Ramesh et al. (2017).

Riga plate is an electromagnetic actuator comprises of permanent magnets and a spanwise aligned array of alternating electrodes mounted on a plane surface (Fig.1). Pantokratoras and Magyari (2009) constructed a basic equation for flow due to riga plate. Pantokratoras (2011) obtained the exact solutions for classical Blasius and Sakiadis problems over a Riga-plate. Further Magyari and Pantokratoras (2011) examined the convection effect on a viscous fluid over a Riga plate. Ahmad et al. (2016) obtained the analytical solution for nanofluid flow over a riga porous plate using perturbation method. Hayat et al. (2016) examined the flow of nanofluid over a Riga plate with variable thickness and convective condition.

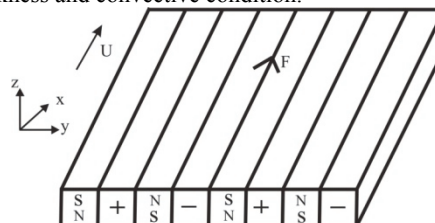


Fig. 1 Riga Plate

The present work we considered the composite velocity and studied the effect of nonlinear radiation on Nanofluid flow past a Riga plate. Similarity transforms are presented for this problem. The coupled nonlinear differential equations have been solved numerically by

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shooting method with fourth–fifth order Runge-Kutta (RK45). Present results are compared with the existing literature. To the best of our knowledge, this problem has not been studied before.

2. MATHEMATICAL ANALYSIS

We consider a laminar, steady two dimensional stretched flow of an electro-magneto hydrodynamic nanofluid over a Riga-plate. Assumed that the plate is moving with a constant velocity U_w and that same or opposite direction to the free stream is U_∞ . Further assume that the surface has a uniform temperature T_w , ambient temperature T_∞ , uniform concentration C_w and ambient concentration C_∞ respectively (see Fig. 2).

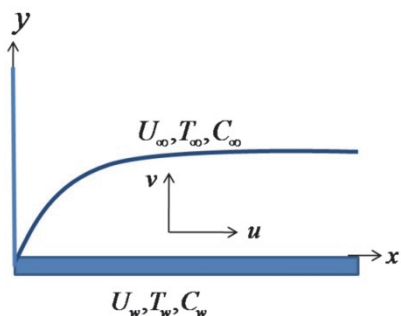


Fig. 2 Sketch of the problem and coordinate system.

With all the assumptions, mathematical equations of the nanofluid flow, the heat and the concentration fields are described in dimensional form as (see Ahmad et al. (2016))

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

$$\left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = \nu \frac{\partial^2 u}{\partial y^2} + \frac{\pi j_0 M_0}{8\rho} \exp\left(-\frac{\pi}{a}y\right) \quad (2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \left(\frac{\partial^2 T}{\partial y^2} \right) \quad (3)$$

$$\left\{ D_B \left(\frac{\partial C}{\partial y} \frac{\partial T}{\partial y} \right) + \left(\frac{D_T}{T_\infty} \right) \left[\left(\frac{\partial T}{\partial y} \right)^2 \right] \right\} - \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y}$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_B \left(\frac{\partial^2 C}{\partial y^2} \right) + \left(\frac{D_T}{T_\infty} \right) \left[\left(\frac{\partial^2 T}{\partial y^2} \right) \right] \quad (4)$$

where u and v are the velocity components along the x and y axes, respectively. Further, α, ρ, ν, T and T_∞ are respectively the thermal diffusivity, density of the base fluid, kinematic viscosity of the fluid, fluid temperature and ambient fluid temperature. j_0 is the applied current density in the electrodes, M_0 is the magnetization of the permanent magnets mounted on the surface of the Riga plate, a is the width of the magnets between the electrodes, D_B is the Brownian diffusion coefficient, D_T is the thermophoresis diffusion coefficient and c_p is the specific heat at constant pressure. Here τ is defined as the ratio of the effective heat capacity of the nanoparticle material and the heat capacity of the ordinary fluid and C is the concentration.

$$\left. \begin{aligned} u = U_w(x), v = 0, T = T_w, C = C_w \text{ at } y = 0 \\ u \rightarrow U_\infty, T \rightarrow T_\infty, C \rightarrow C_\infty \text{ as } y \rightarrow \infty, \end{aligned} \right\} \quad (5)$$

Expression of radiative heat flux can be defined, using Rosseland approximation is

$$q_r = -\frac{4\sigma^*}{3k^*} \frac{\partial T^4}{\partial y} = \frac{16\sigma^*}{3k^*} T^3 \frac{\partial T}{\partial y} \quad (6)$$

where σ^* is the Stefan-Boltzmann constant, k^* is the mean absorption coefficient. Here in equation (6) T is highly nonlinearity, and our main objective is to study the behavior of non-linear thermal radiation. Thus, using Pantokratoras and Fang (2013) the energy equation (3) will take the following form:

$$\begin{aligned} u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\partial}{\partial y} \left[\left(\alpha + \frac{16\sigma^*}{3k^*} T^3 \frac{\partial T}{\partial y} \right) \frac{\partial T}{\partial y} \right] \\ + \tau \left\{ D_B \left(\frac{\partial C}{\partial y} \frac{\partial T}{\partial y} \right) + \left(\frac{D_T}{T_\infty} \right) \left[\left(\frac{\partial T}{\partial y} \right)^2 \right] \right\} \end{aligned} \quad (7)$$

Composite velocity is described as $U = U_w + U_\infty$ (Afzal et al. (1993)), we now introduce the similarity function ψ , which satisfies the governing continuity Eq. (1) as:

$$u = \frac{\partial \psi}{\partial y} \text{ and } v = -\frac{\partial \psi}{\partial x}, \quad (8)$$

and similarity solution of Eqs. (1),(2), (7) and (4) of the following form

$$\eta = \sqrt{\frac{U}{\nu x}} y, \psi = \sqrt{U \nu x} f(\eta), \quad (9)$$

$$\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}$$

where $T = T_\infty (1 + (\theta_w - 1)\theta)$ and $\theta_w = \frac{T_w}{T_\infty}$ is the temperature ratio

parameter (Shehzad et al. (2014)). Using the above relation (9) in Eqs. (2), (7) and (4), one can get the following non-dimensional equations

$$f''' + \frac{1}{2} f f'' + Q \exp(-\eta\beta) \quad (10)$$

$$\left[\left[1 + Nr(1 + (\theta_w - 1)\theta)^3 \right] \theta' \right]' + \text{Pr} \left[\frac{1}{2} f \theta' + Nb \theta' \phi' + Nt \theta'^2 \right] = 0 \quad (11)$$

$$\phi'' + \frac{1}{2} f \phi' Sc + \frac{Nt}{Nb} \theta'' = 0 \quad (12)$$

Corresponding boundary conditions will becomes

$$\left. \begin{aligned} f = 0, f' = \lambda, \theta = 0, \phi = 0 \text{ at } \eta = 0, \\ f' \rightarrow 1 - \lambda, \theta \rightarrow 0, \phi \rightarrow 0 \text{ as } \eta \rightarrow \infty, \end{aligned} \right\} \quad (13)$$

Prime denotes the derivative with respect to η , and Q is the modified Hartman number, β is the dimensionless parameter, Nr is the radiation parameter, Nt is the thermophoresis parameter, Nb is the Brownian motion parameter, Sc is the Schmidt number, Pr is the Prandtl number and λ is the velocity ratio parameter and they are defined as

$$Q = \frac{x \mu j_0 M_0}{8 \rho U^2}, \beta = \frac{\pi}{a \left(\frac{U}{\nu x} \right)^{1/2}}, Nr = \frac{16 \sigma^* T_\infty^3}{3 k k^*}, Nt = \frac{\tau D_T}{\nu T_\infty} (T_w - T_\infty),$$

$$Nb = \frac{\tau D_B}{\nu} (C_w - C_\infty), Sc = \frac{\nu}{D_B}, \text{Pr} = \frac{\alpha}{\nu}, \lambda = \frac{U_w}{U}$$

As we note that when $\lambda = 0$ the problem reduces to Blasius flow i.e., flow induced over a stationary flat-plate by a uniform free stream and when $\lambda = 1$ the problem reduces to Sakiadis flow i.e., flow induced by a moving plate in a quiescent ambient fluid. The skin friction coefficient, local Nusselt number and local Sherwood number are the physical quantities defined as.

$$C_f = \frac{\tau_w}{\rho U_w^2}, Nu_x = \frac{xq_w}{\alpha(T_w - T_\infty)}, Sh_x = \frac{xq_m}{D_B(C_w - C_\infty)} \quad (14)$$

where the shear stress τ_w , surface heat flux q_w and surface mass flux q_m are given by

$$\tau_w = \mu \left(\frac{\partial u}{\partial y} \right)_{y=0}, q_w = -\alpha \left(\frac{\partial T}{\partial y} \right)_{y=0} \text{ and } q_m = -D_B \left(\frac{\partial C}{\partial y} \right)_{y=0} \quad (15)$$

Using the non-dimensional variables, we obtain

$$C_f Re_x^{1/2} = f''(0), \frac{Nu_x}{Re_x^{1/2}} = -(1 + Nr\theta_w^3)\theta'(0), \frac{Sh_x}{Re_x^{1/2}} = -\phi'(0) \quad (16)$$

3. RESULTS AND DISCUSSION

The coupled ordinary non-linear differential equations (10) to (12) along with the boundary conditions (13) were solved numerically using Runge-Kutta-Fehlberg 45 order method by adopting shooting technique [see Ramesh and Gireesha (2014)]. These equations are transformed into seven first order expressions involving fourteen unknowns. The missed initial conditions are found with help of shooting method. In order to validate our numerical solution, we have constructed Table 1. This table showed that comparative study of present results with the existing results. Impacts of various parameters on the velocity, temperature and concentration profiles are analyzed. Figs. 3-13 have been plotted in this regard.

Key parameter of the present study is modified Hartman number. Fig. 3 exhibits the effect of modified Hartman number (Q) on the dimensionless velocity, temperature and concentration. It is clearly noted that the velocity profile of the nanofluid is significantly increased with increase of Q whereas opposite effect are found in temperature and concentration. Physically large values of modified Hartman number results in the development of external electric field which consequently enhances the velocity distribution characteristics. Figs. 4 and 5 are prepared to shows the effect of β on dimensionless velocity, temperature and concentration profiles. It is noticed that temperature and concentration of both profiles are significantly increases with the increasing of β whereas opposite effect are found in velocity profile.

The behavior of Brownian motion parameter Nb on dimensionless temperature and concentration are plotted in Figs. 6 and 7. The temperature profile is increasing functions of Brownian motion number Nb whereas the concentration profile is decreasing function. Figs. 8 and 9 reveal the dimensionless temperature and concentration in response to a change in thermophoresis parameter Nt . As increase of Nt values, the temperature and concentration boundary layer thickness is also increases. From Fig. 10, as Schmidt number Sc increases the concentration diagram decreases and also boundary layer thickness decreases. Further the graph reveals that the concentration gradient at surface is increases. Physical reason is larger values of Sc have a stronger viscous diffusion which increases the molecular motions hence the temperature increases.

Table-1: Comparison results of $f''(0)$ for different values of λ in the absence of Sc, Nb, Nr, Nt, Pr, Q and β .

λ	Blasius (1908)	Sakiadis (1961)	Ishak et al. (2011)	Mukhopadhyay et al. (2011)	Present results
0.0	0.332	---	0.3321	0.332060	0.33205
1.0	---	-0.4437	-0.4438	-0.443751	-0.44390

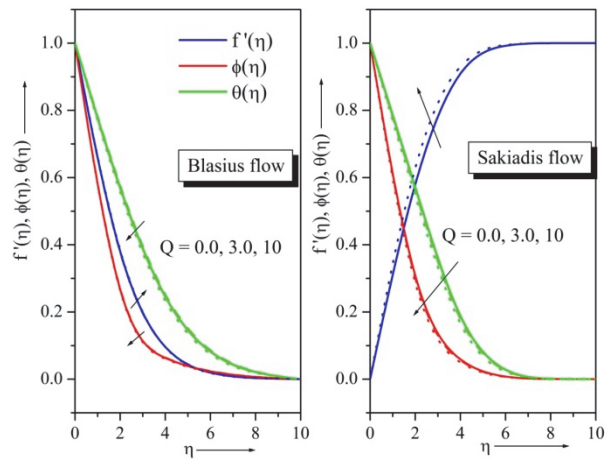


Fig. 3 Effect of Q on velocity, temperature and concentration profiles

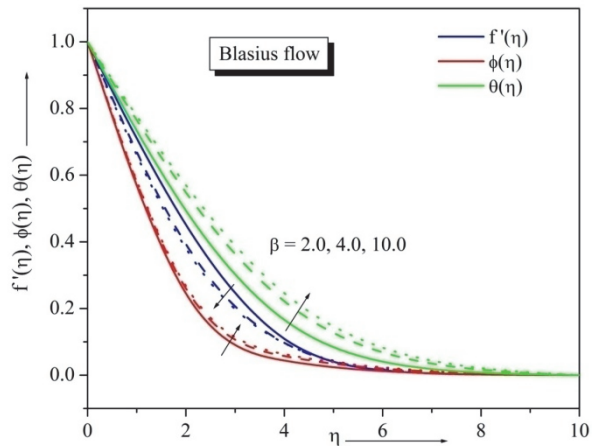


Fig. 4 Effect of β on velocity, temperature and concentration profiles

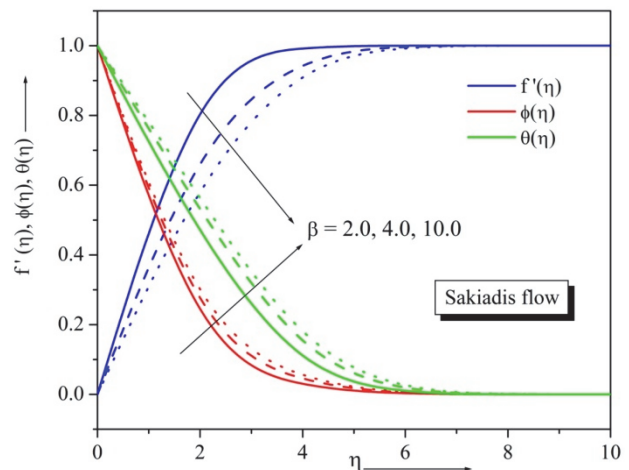


Fig. 5 Effect of β on velocity, temperature and concentration profiles

Effects of radiation Nr on temperature profile is depicts in Fig. 11. One can observed that $\theta(\eta)$ shows the increasing behavior with increasing values of Nr . And θ_w has to be larger value than one. Therefore, it is expected to have a higher temperature and a thicker thermal boundary layer with increasing values of θ_w .

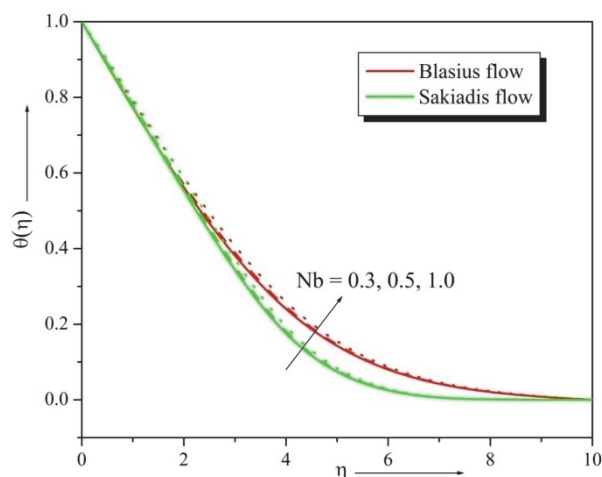


Fig. 6 Effect of Nb on temperature profile

The curves of temperature $\theta(\eta)$ for various Prandtl number are described in Fig. 12. We examined that the lower Prandtl number has higher profiles $\theta(\eta)$ and associated thickness of boundary layer. The diffusivity of liquid is appeared in Prandtl number that becomes weaker for higher Pr. The influence of velocity ratio parameter λ on velocity, temperature and concentration profile are presented in Fig. 13. When we increasing the values of velocity ratio parameter simultaneously fluid velocity decreases, temperature increases and concentration decreases.

From Table 2 it is noted that $f''(0)_{Blasius} > f''(0)_{Sakiadis}$, $-\phi'(0)_{Blasius} < -\phi'(0)_{Sakiadis}$ and $-\theta'(0)_{Blasius} < -\theta'(0)_{Sakiadis}$

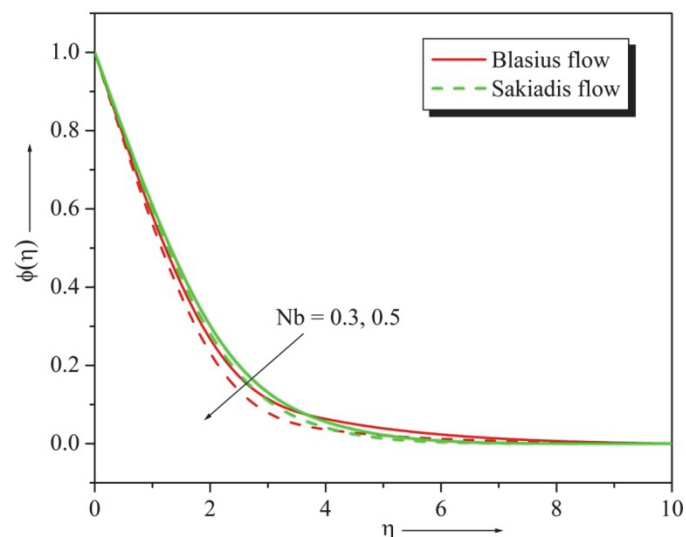


Fig. 7 Effect of Nb on concentration profile.

4. CONCLUSIONS

We study the behavior of nonlinear thermal radiation on a boundary layer flow of nanofluid over a Riga plate. Here we studied the two type problems namely classical Sakiadis flow (stationary plate) and Blasius flow (moving plate). The following points are worth mentioning.

- Velocity increases, temperature and concentration decreases when the modified Hartman number increases.
- Temperature increases when temperature ratio parameter increases.

- Increasing values of thermophoresis and Brownian motion parameters creates an enhancement in temperature profile because of higher thermal conductivity fluid.
- Skin friction values of Blasius flow always higher than the Sakiadis flow.

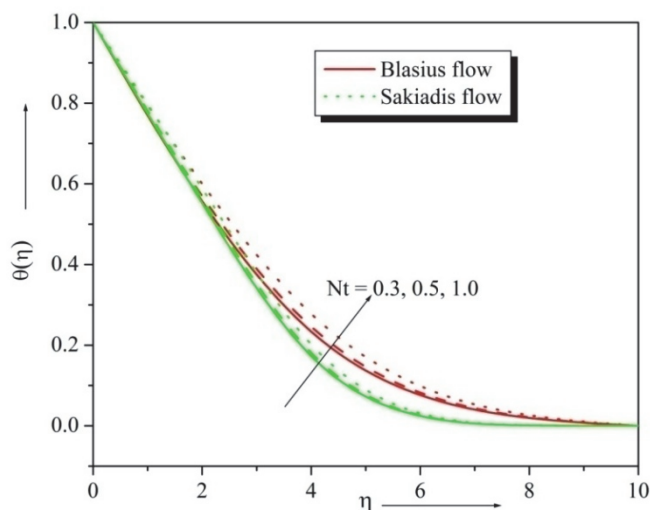


Fig. 8 Effect of Nt on temperature profile.

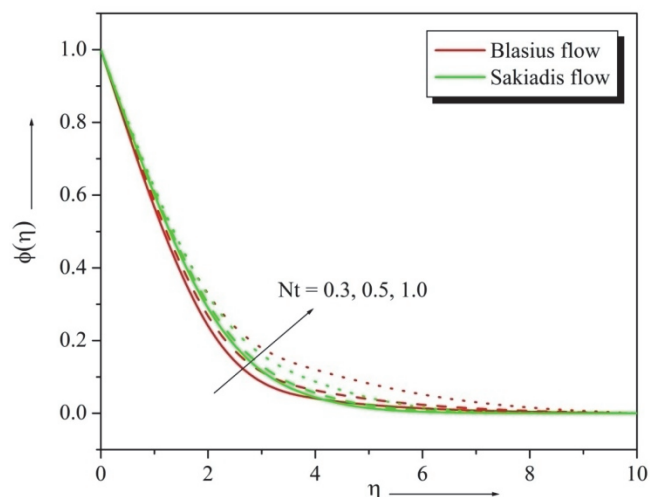


Fig. 9 Effect of Nt on concentration profile

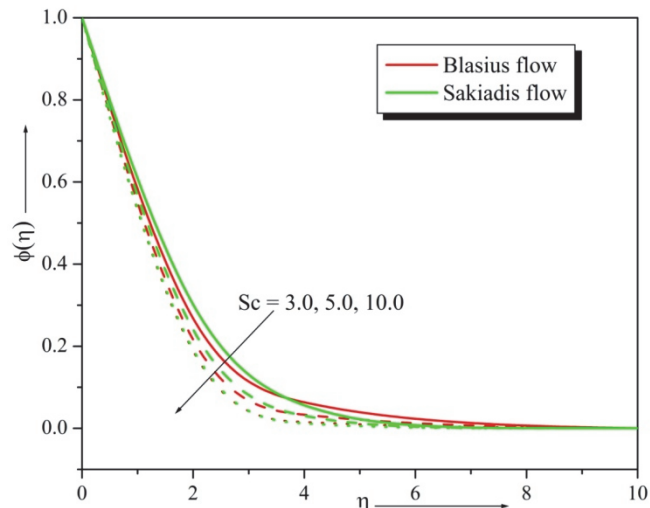


Fig. 10 Effect of Sc on concentration profile.

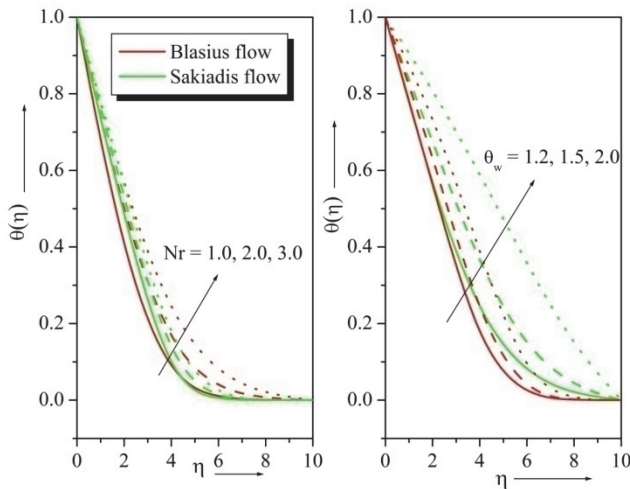


Fig. 11 Effect of Nr and θ_w on temperature profiles

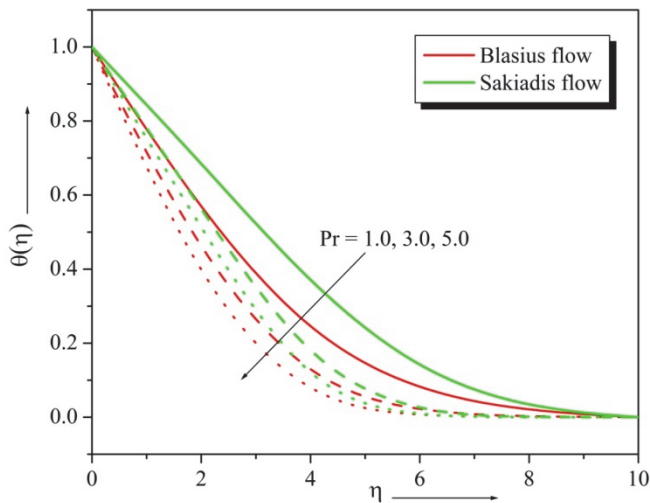


Fig. 12 Effect of Pr on temperature profile

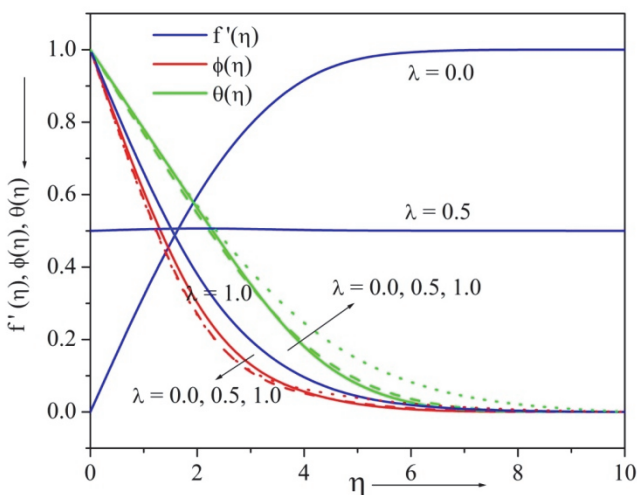


Fig. 13 Effect of λ on velocity, temperature and concentration profiles

Table-2: Computation Values of $-f''(0)$, $-\theta'(0)$ and $-\phi'(0)$ for different values of Q with $Sc = 3, Nb = 0.5, Nr = 3, Nt = 0.5, Pr = 3, \theta_w = 1.2$ and $\beta = 10$.

Q	Sakiadis flow			Blasius flow		
	$-f''(0)$	$-\phi'(0)$	$-\theta'(0)$	$f''(0)$	$-\phi'(0)$	$-\theta'(0)$
0.0	0.44390	0.81143	0.18992	0.33205	0.50353	0.17043
0.1	0.43449	0.81176	0.19000	0.34202	0.50411	0.17055
0.5	0.39688	0.81308	0.19034	0.38188	0.50642	0.17105
0.8	0.36867	0.81407	0.19059	0.41176	0.50814	0.17141
1.0	0.34986	0.81472	0.19076	0.43168	0.50929	0.17166

NOMENCLATURE

- a width of the magnets between the electrodes
- c Concentration (kg/m^3)
- c_p Specific heat ($J/kg K$)
- c_w concentration at wall
- c_∞ ambient concentration
- D_B Brownian diffusion coefficient
- D_T thermophoresis diffusion coefficient
- f dimensionless stream function
- j_0 applied current density in the electrodes
- k thermal conductivity ($W/m K$)
- k^* mean absorption coefficient (m^{-1})
- M_0 magnetization of the permanent magnets
- Nr radiation parameter
- Nb Brownian motion parameter
- Nt thermophoresis parameter
- Pr Prandtl number
- Q modified Hartman number
- Sc Schmidt number
- T temperature of the fluid (K)
- T_w uniform temperature (K)
- T_∞ ambient temperature (K)
- U_w constant velocity
- U_∞ free stream velocity
- u, v velocity components of the fluid along x and y directions
- x, y Cartesian co-ordinates

Greek Symbols

- α thermal diffusivity (m^2/s)
- β dimensionless parameter
- λ velocity ratio parameter
- ρ density of the base fluid (kg/m^3)
- ν kinematic viscosity of the fluid (m^2/s)
- σ^* Stefan-Boltzmann constant ($W/m^2 K^4$)
- θ dimensionless fluid temperature
- θ_w temperature ratio parameter
- μ viscosity of the fluid ($N s/m^2$)
- η similarity variable

Subscripts

- w at the wall
- ∞ ambient temperature

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