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P.Mohan Krishna, Ram Prakash Sharma, N. Sandeep

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Boundary layer analysis of persistent moving horizontal needle in Blasius and Sakiadis MHD radiative nanofluid flows

P.Mohan Krishna[1] Ram Prakash Sharma[2] N.Sandeep[3*]

[1] Department of Humanities and Sciences, Sri Venkateswara College of Engineering and Technology, Chittoor-517 127, India.
[2]Department of Mathematics, JECRC University, Jaipur-303905, Rajastan, India.
[3] Department of Mathematics, VIT University, Vellore-632014, India.
[3]Email **:** dr.nsrh@gmail.com

Abstract:

The boundary layer of a 2D forced convective flow along a persistent moving horizontal needle in an electrically conducting magneto hydrodynamic dissipative nanofluid was numerically investigated. The energy equation was constructed with joule heating, viscous dissipation, uneven heat source/sink and thermal radiation effects. We analyzed the boundary layer behavior of a continuously moving needle in Blasius (moving fluid) and Sakiadis (quiescent fluid) flows. We considered Cu-nanoparticles embedded in methanol. The reduced system of governing PDEs was solved by employing the Runge-Kutta based shooting process. The computational outcomes of the rate of heat transfer and friction factors were tabulated and discussed. Velocity and temperature descriptions were examined with the assistance of graphical illustrations. Increasing the needle size did not have a significant influence on the Blasius flow. The heat transfer rate in the Sakiadis flow was high compared to the Blasius flow.

Keywords: MHD; Nanofluid; Heat Transfer;Dissipation;Joule heating;Radiation.

1. Introduction

Nanofluids have advantages in a broad range of technical applications, and their characteristics are of interest in both science and engineering. Nanofluid technologies have potential benefits in solar energy, heat transfer fluids (cooling or heating), nuclear reactors, etc. Accordingly, in recent decades a significant number of investigators have been engaged in studying nanofluid applications in various fields. Choi [1], for example, developed the concept of nanofluids in cooling technologies.

Among such studies, many researchers have been energetically involved in solving the problem of boundary layer flows past thin needles, including Agarwal et al. [2], Kumari and Nath [3], Ishak et al. [4], Ahmad et al. [5], Takhar et al. [6], Cebeci and Na [7] and Patil et al. [8]. Rashid Mehmood et al. [9] analyzed the oblique flow of a Jeffery nanofluid along a stretching plate. The influence of the porosity of the uniform stream, and the quiescent ambient fluid motion of a nanofluid under a convective boundary condition, were studied by Hady et al. [10]. Makinde [11] conducted an analysis of the quiescent ambient fluid flow of nanofluids in the presence of Newtonian heating and viscous dissipation.

Makinde and Aziz [12] investigated the numerical solution of the induced laminar flow of nanofluids past a linearly stretching sheet. Sandeep et al. [13] investigated the free convective motion of nanofluids past an impulsively vertical surface. Mohan Krishna et al. [14] studied the same topic and extended the study by adding a heat source and various nanofluids. Sandeep [15] discussed the convective heat transfer in a MHD liquid film flow. The impact of internal friction and radiation on the Sakiadis and Blasius motions under the surface boundary condition was analyzed by Olanrewaju et al. [16]. Awais et al. [17] studied the magnetohydrodynamics of a coupled stress nanofluid over a stretching sheet in the presence of a convective wall. Ambethkar [18] discussed the impact of an unsteady magnetohydrodynamic natural convective motion over a vertical surface under the influence of constant suction. Nadeem et al. [19] discussed the stagnation point flow of a nanofluid using phase flow and Buongiorno models.

Mohan Krishna et al. [20] investigated the magnetohdrodynamic boundary layer motion of a vertical surface in the presence of a heat source. Ibrahim and Makinde [21] investigated the impact of a chemical reaction on the laminar natural convective motion of a rotating vertical sheet with suction. Sulochana et al. [22] and Jones et al. [23] investigated the effect of an aligned magnetic field on laminar flow through various channels. Khan and Pop [24] conducted a numerical study of the boundary layer motion of a nanofluid past a stretching flat surface. Bhattacharya et al. [25] explored the numerical solution of an unsteady magnetohydrodynamic laminar flow past a stretching sheet under the assumption of suction/blowing, with chemical reaction and power-law variation in the wall concentration. Ramesh et al. [26] examined the boundary layer motion on the transfer of heat in a dusty fluid past a permeable stretching surface under the influence of a thermal radiative effect. [26]. The transfer of heat and the unsteady laminar motion of a stretching surface has been discussed by Sharidan et al. [27]. Siddiqa et al. [28] performed studies on the heat and mass transfer of a nanofluid with a bioconvective flow along a vertical cone. Very recently, the researchers [29-31] studied the heat and mass transfer nature of MHD flows over various geometries. The heat and mass transfer characteristics of a magnetohydrodynamic non-Newtonian nanofluid flow over different geometries was studied by [32-35].

In this study, a two-dimensional forced convective flow along a persistent moving horizontal needle in an electrically conducting magneto hydrodynamic dissipative nanofluid was numerically investigated. The energy equation was constructed with joule heating, viscous dissipation and non-uniform heat source/sink effects. We have analyzed the boundary layer behavior of a continuously moving needle in Blasius (moving fluid) and Sakiadis (quiescent fluid) flows. We considered Cu-nanoparticles embedded in methanol. The reduced system of governing PDE's was solved by employing the Runge-Kutta based shooting process.

2. Mathematical formulation

Consider the steady, forced convective magnetohydrodynamic Newtonian nanofluid motion under the stagnation region of a thin needle. Fig.1 shows the cylindrical coordinates (x,r) such that the x-axis is the axial direction and r is normal to the x-axis and termed the radial direction, while c is the magnitude of the needle. We examined the flow with the assistance of thermal stratification. We assumed that the temperature of the cylindrical surface T_w was much greater than the ambient fluid, and T_w and T_∞ are constants where $T_w > T_\infty$ (heated needle). Also, $U_0 = u_w + u_\infty$ is the composite velocity along the x-axis, and the needle moves with constant velocity u_w. The mainstream of constant velocity is u_∞. The electromagnetic field B_0 is imposed parallel to the direction of motion and the induced magnetic field is neglected. Joule heating, and te uneven heat source/sink are taken into account.

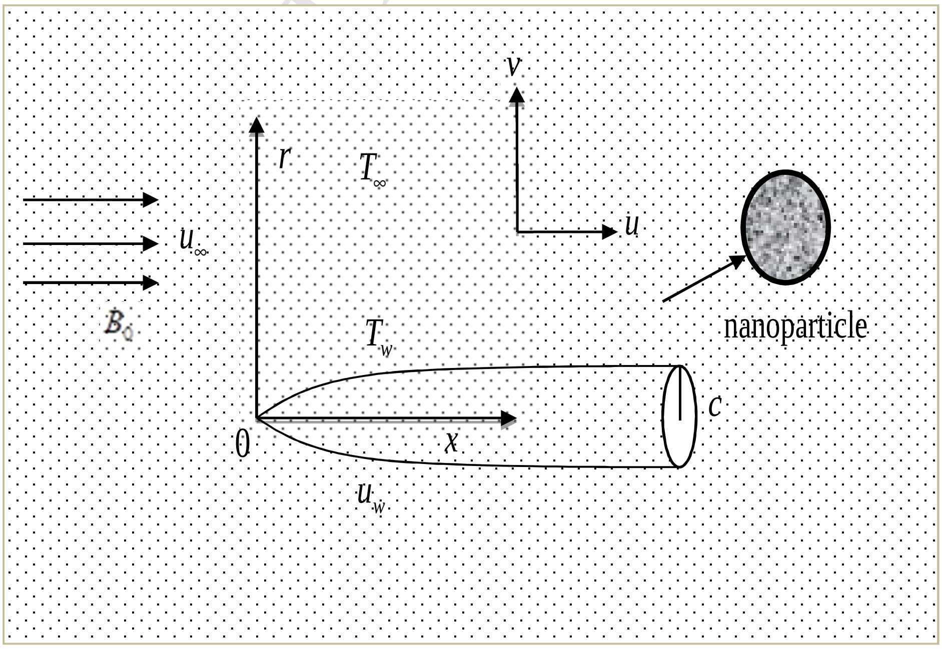

Fig. 1 Schematic representation

Under the above conditions and in the absence of a pressure gradient, we imposed the governing equations as

$$(ru)_x+(rv)_r=0 \tag{1}$$

$$\rho_{nf}\left(uu_x+vu_r\right)=\mu_{nf}\frac{1}{r}\left(ru_r\right)_r-\sigma B_0^2u \tag{2}$$

$$(\rho C_p)_{nf}\left(uT_x+vT_r\right)=\frac{1}{r}\left[\left(k_{nf}\right)\left(rT_r\right)\right]_r+q'''+\sigma B_0^2u^2+\mu_f\left(u_r\right)^2-\frac{16\sigma^*T_\infty^{\ 3}}{3k^*}T_{rr} \tag{3}$$

The suitable boundary conditions are,

$$\begin{aligned}&u=u_w, T=T_w\ \ v=0,\ \text{at } r=R(x)\\&T\to T_\infty\ , u\to u_\infty, \qquad \text{as } r\to\infty\end{aligned} \tag{4}$$

where, u,v are velocities in the axial and radial (x,r) directions, respectively. $(\rho C_p)_{nf}, k_{nf}, \rho_{nf}, \mu_{nf}$ are the specific heat capacity, thermal conductivity, effective density and viscosity of the nanofluids, which are given as (see Ref. [15])

$$\left.\begin{aligned}&k_{nf}=\left(\frac{k_s+2k_f-2\phi k_f+2\phi k_s}{k_s+2k_f+2\phi k_f-2\phi k_s}\right)k_f,\\&\rho_{nf}=\rho_f-\phi\rho_f+\phi\rho_s, \mu_{nf}=\mu_f(1-\phi)^{-2.5},\\&(\rho C_p)_{nf}=(\rho C_p)_f-\phi(\rho C_p)_f+\phi(\rho C_p)_s,\end{aligned}\right\} \tag{5}$$

The non-uniform heat source/sink is stated as $q'''=\left(k_fU_0(T_w-T_\infty)/xv_f\right)\left[A^*f'+B^*\frac{(T-T_\infty)}{(T_w-T_\infty)}\right]$.

To compute the basic Eqns. (1) to (3) under the boundary restrictions (4), we assumed the relevant transformations as follows,

$$\psi=v_fxf(\eta), \eta=U_0r^2/v_fx, \theta(\eta)=(T-T_\infty)/(T_w-T_\infty), \tag{6}$$

Here, ψ is defined as a stream function which satisfies the continuity Eqn. (1) exactly, and the velocity components are defined as $u=r^{-1}\psi_r, v=-r^{-1}\psi_x$. Assume, $\eta=c$ in Eqn. (6) predicts the magnitude of the needle $r=R(x)=\sqrt{v_fcx/U_0}$ along the surface. Using Eqn. (6) in basic Eqns. (2) to (4) reduces to the following nonlinear differential form,

$$2(1-\phi)^{-2.5}(f'''\eta+f'')+(1-\phi+\phi\frac{\rho_s}{\rho_f})(ff''-Mf')=0 \tag{7}$$

$$2\left(\frac{k_{nf}}{k_f}+R\right)(\theta''\eta+\theta')+\left(1-\phi+\phi\frac{(\rho C_p)_s}{(\rho C_p)_f}\right)\Pr f\theta'+(A^*f'+B^*\theta)+Ec(2\eta f''^2+Mf'^2)=0 \tag{8}$$

The suitable boundary conditions are,

$$\begin{aligned} &f(c) = c\lambda/2,\, f\,'(c) = \lambda/2, \theta(c) = 1, \\ &f\,'(\eta) \to 1 - \lambda/2, \theta(\eta) \to (\lambda/2) \ \text{ as } \eta \to \infty \end{aligned} \tag{9}$$

where $\lambda = u_w/U_0$ is defined as the ratio of the velocity of the needle and the composite velocity. Here, $\lambda = 0$ and $\lambda = 1$ relate to a fixed needle in a moving fluid (Blasius flow), and a moving needle in a stationary fluid (Sakiadis flow), respectively. In this study $\lambda \leq 1$ is restricted to all boundary conditions, i.e., a free stream always moves in a positive direction. The physical parameters $M, \mathrm{Pr}, A^*, B^*, Ec$ and R denote the magnetic field, Prandtl number, non-uniform heat source/sink, disssipation and thermal radiation, respectively. They are described as

$$M = \frac{\sigma B_0^2}{2\rho U_0}, \mathrm{Pr} = \frac{\mu C_p}{k_f}, Ec = \frac{2U_0{}^2}{C_p(T_w - T_\infty)}, R = \frac{16\sigma^* T_\infty^3}{3k^* k} \tag{10}$$

The friction factor is given by,

$$\mathrm{Re}_x^{1/2}\, C_f = 4c^{1/2}(1-\phi)^{-2.5} f\,''(c), \tag{11}$$

The Nusselt number is given by,

$$\mathrm{Re}_x^{-1/2}\, Nu_x = \left(-2c^{1/2} K_{nf} / K_f\right) \theta\,'(c), \tag{12}$$

where $\mathrm{Re}_x = U_0 x / \nu_f$.

3. Results and Discussion

The nonlinear ODE Eqs. (7) and (8) with suitable restrictions Eq. (9) are unravelled by applying the Runge-Kutta based shooting process. For computational purposes, the non-dimensional constants are used throughout the study as $A^* = B^* = c = 0.1;\ \phi = 0.01; \mathrm{R} = 0.5;$ $M = 1; Ec = 0.1; \lambda = 1$. Figs. 2 and 3 represent the effect of the magnetic parameter (M) on the velocity and temperature descriptions. It has been noticed that as the value of the magnetic parameter (M) rises, the velocity description reduces and increases the temperature descriptions for both the Sakiadis and Blasius motion cases. In general, larger values of (M) enhance the divergent force of motion known as the Lorentz force. This type of impact has a tendency to reduce the velocity profiles and increase the thermal boundary layers.

Figs. 4 and 5 display the effect of (ϕ) on the velocity and temperature descriptions, respectively, for both the Sakiadis and Blasius motion investigations. It has been observed that the velocity decreases and temperature is enhanced as the increase in the volume fraction (ϕ) occurs for both the Sakiadis and Blasius flow cases. The temperature description for various values of non-uniform heat source/sink are illustrated in Figs. 6 and 7 for both the Sakiadis and Blasius flow cases. It can be seen from the figures that an increase in the non-uniform heat source/sink parameters increases the temperature descriptions for both the Sakiadis and Blasius flow cases. This is consistent with the common physical conduction in a heat source/sink where the non-negative values of $\left(A^*\right)$ and $\left(B^*\right)$ behave like heat generators, and negative values act as heat absorbers. Typically, enhancement of the heat source will exceed the thermal and velocity boundary layer thickness.

The temperature descriptions for various values of Eckert number are illustrated in Fig. 8 for the Sakiadis and Blasius flow cases. It is noted that the temperature and thermal boundary layer thicknesses are enhanced by an increase in the values of Eckert number for both the Sakiadis and Blasius flows investigations. This may be due to the increasing viscosity of the fluid. Figs. 9 and 10 show the effect of needle thickness parameter c on the velocity and temperature profile, respe**c**tively, for both the Sakiadis and Blasius flow investigations. It can be seen that the velocity and temperature descriptions decline with the increment in needle parameter c for both the Sakiadis and Blasius flow cases.

Tables 1 and 2 depict the variations in wall friction and local Nuseelt number for the Sakiadis and Blasius flows. It is clear that the rising values of the volume fraction of the nanoparticles enhances the heat transfer rate of the Sakiadis flow. But this trend is reversed for the Blasius flow. The increase in film thickness enhances the local Nusselt number in both cases. Increasing the magnetic field parameter reduces the wall friction. The uneven heat source/sink parameters reduce the heat transfer rate. Table 3 presents the thermal and physical properties. Table 4 shows the validation of the numerical procedure.

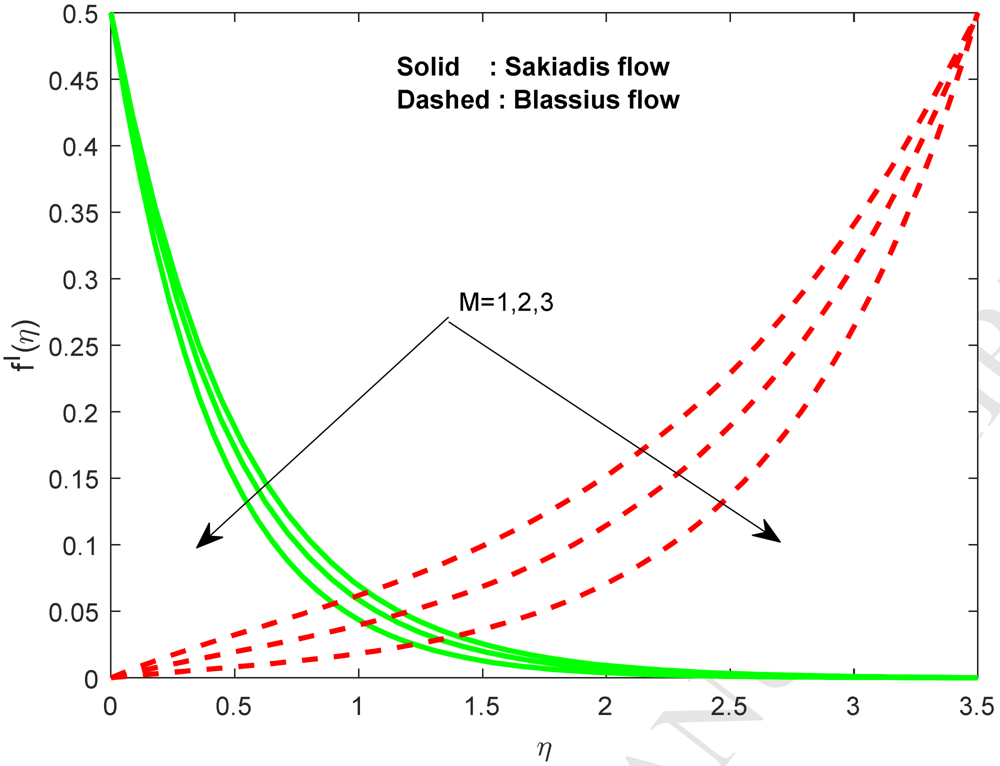

Fig.2 Velocity profiles v/s parameter M

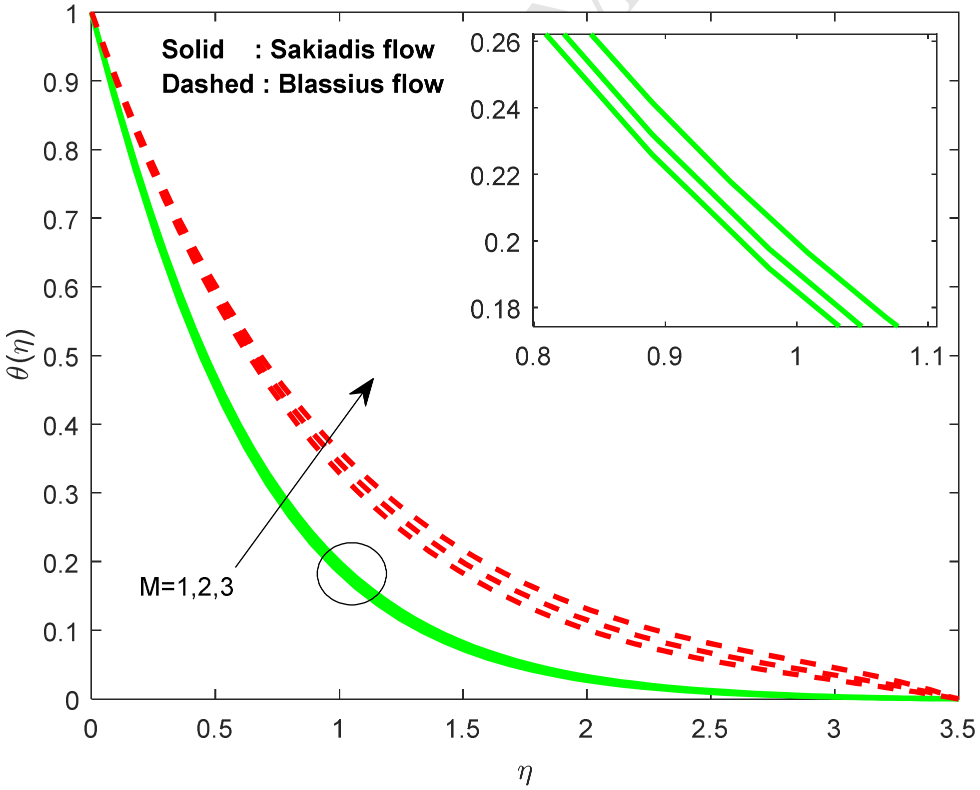

Fig.3. Temperature profiles v/s parameter M

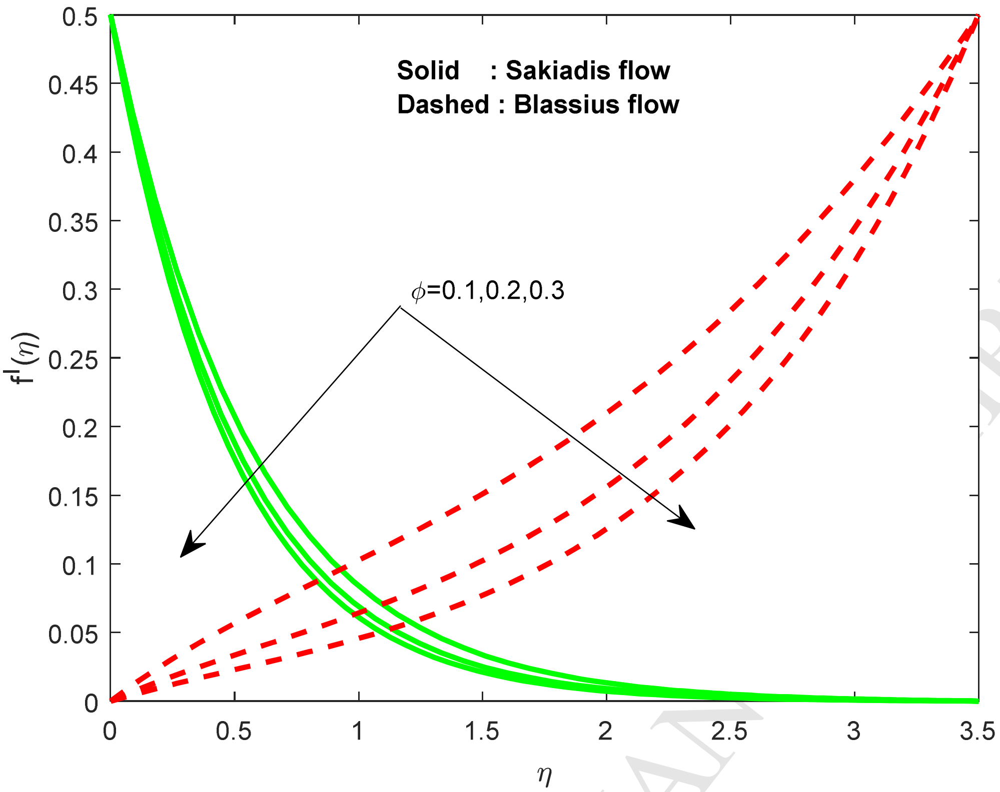

Fig.4.Velocity profiles v/s volumetric fraction ϕ

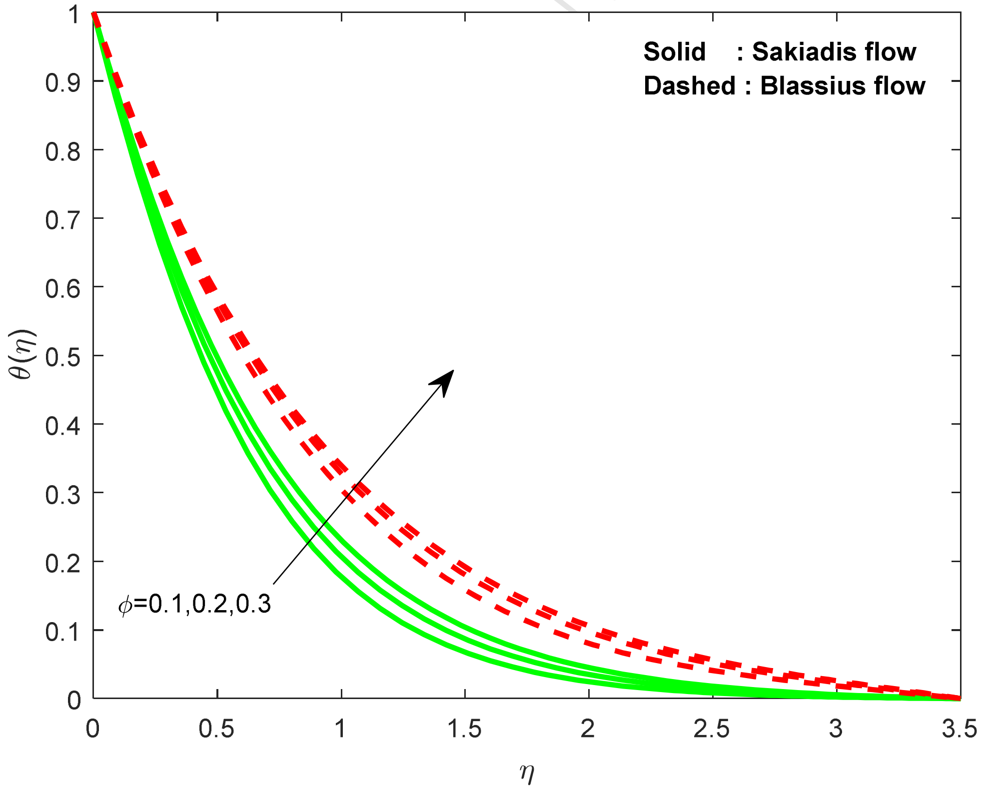

Fig.5. Temperature profiles v/s volumetric fraction ϕ

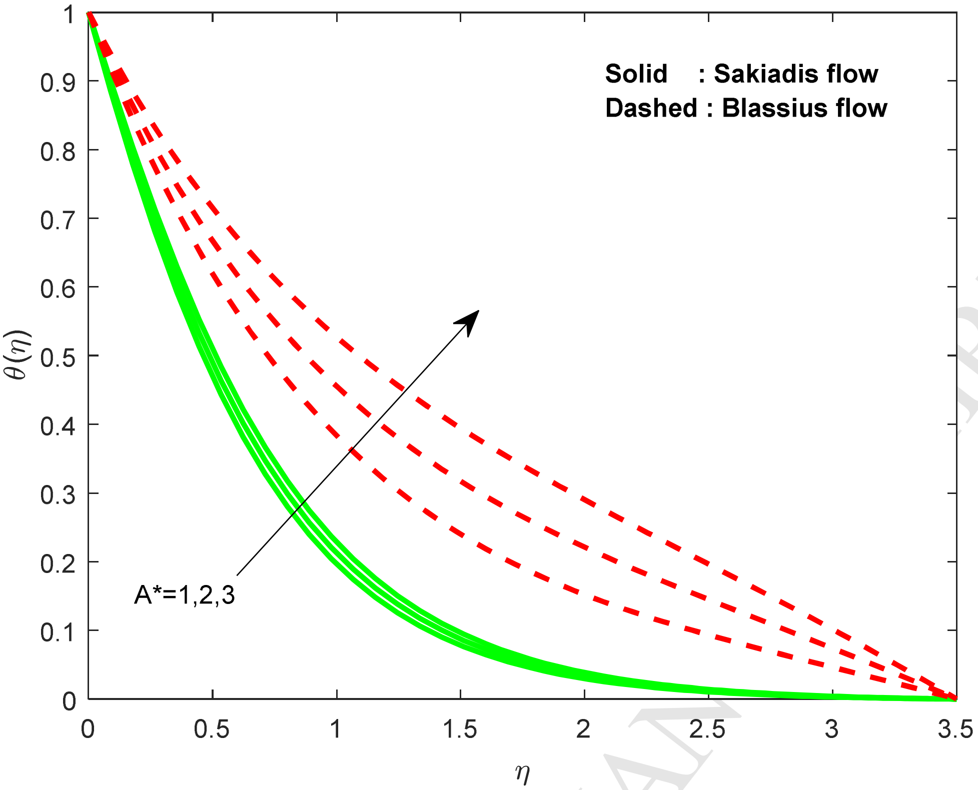

Fig.6. Temperature profiles v/s heat source/sink

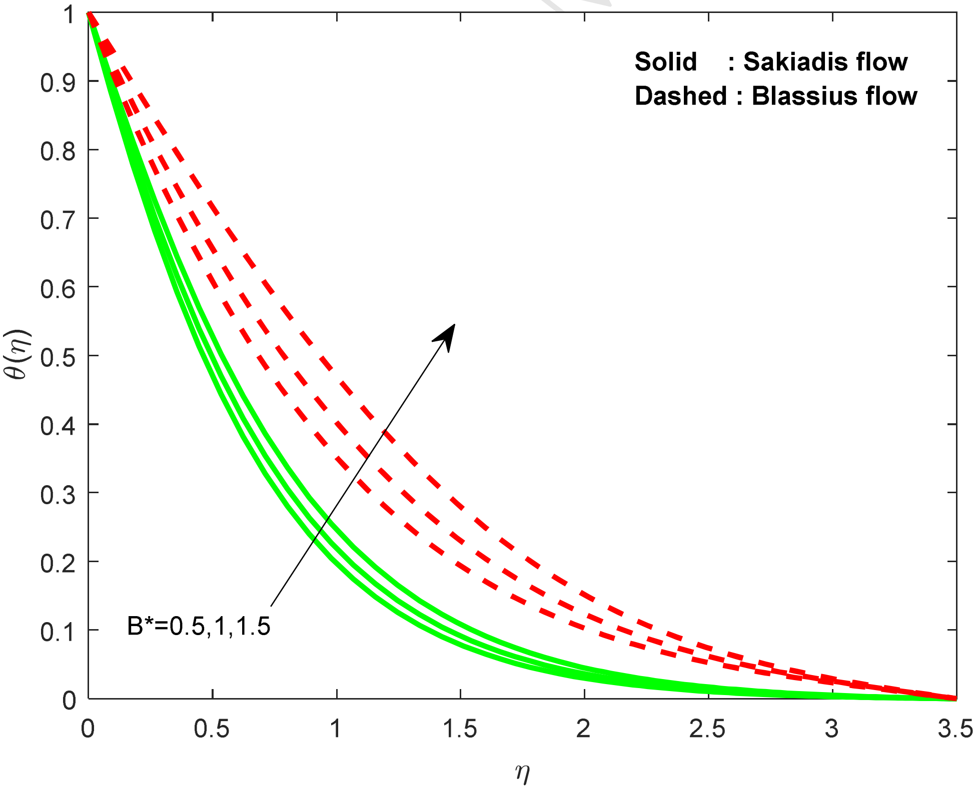

Fig.7.Temperature description v/s heat source/sink

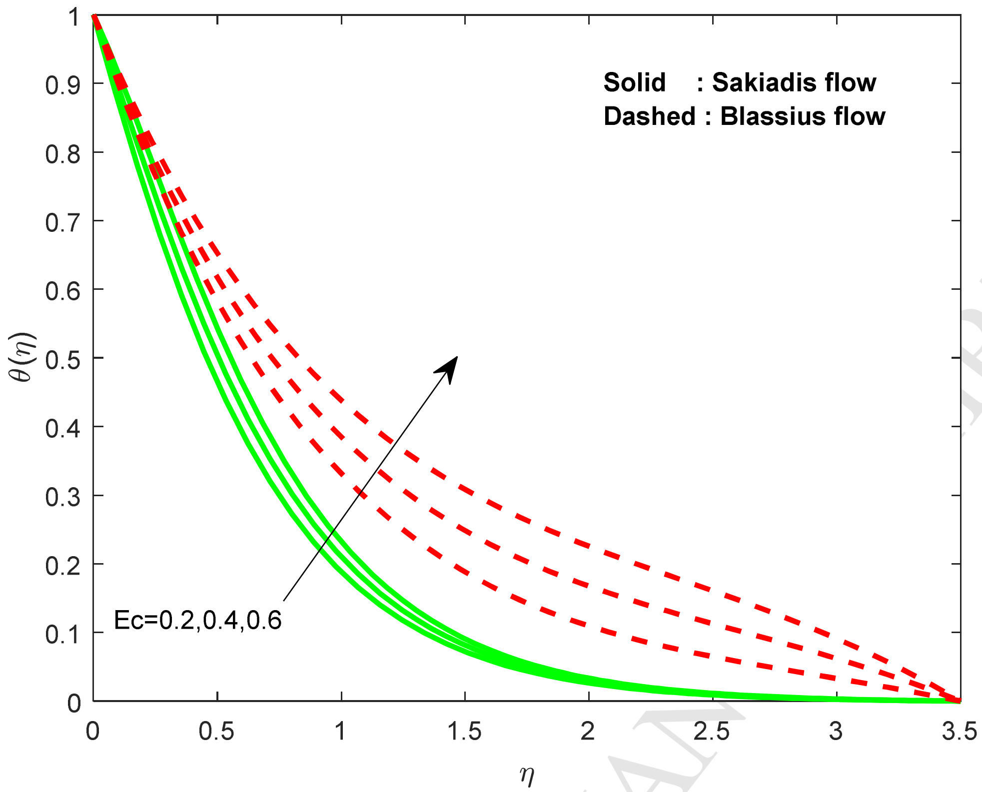

Fig.8. Temperature description v/s Eckert number

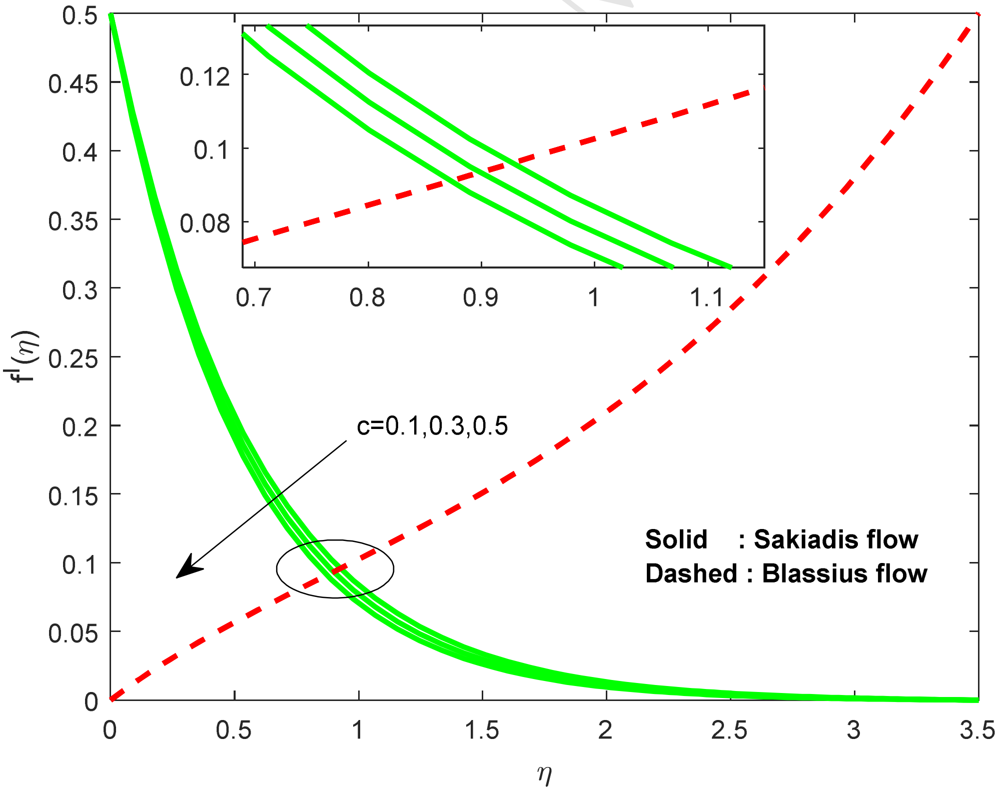

Fig.9.Velocity profiles v/s needle thickness

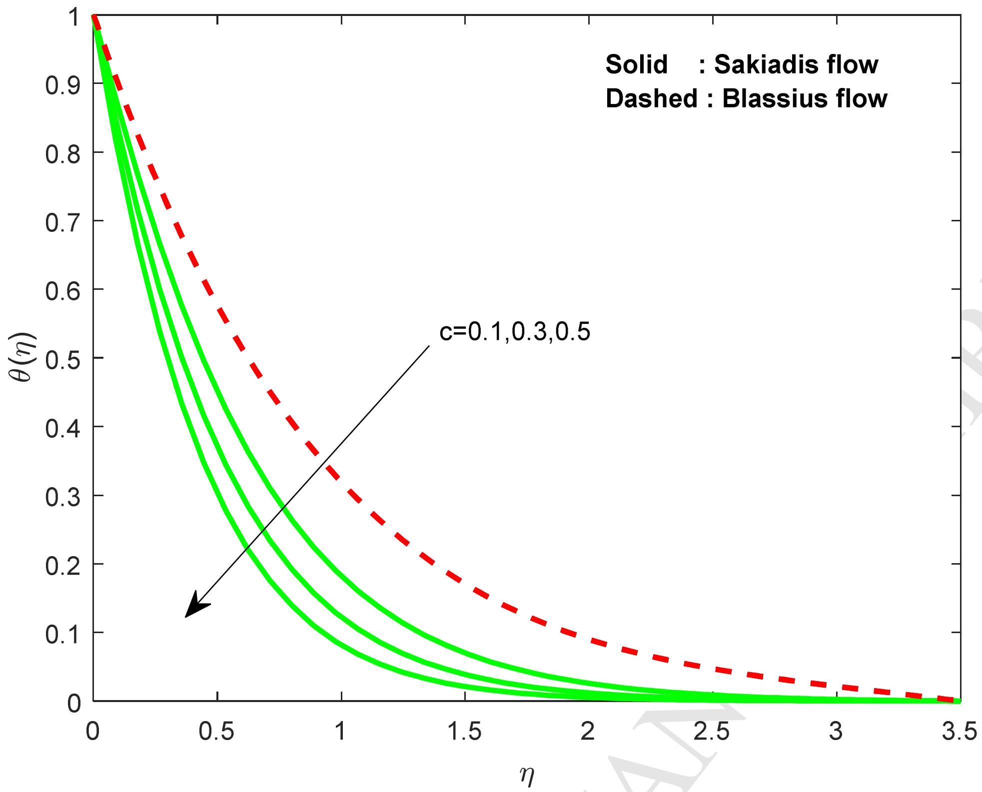

Fig.10. Temperature profiles v/s needle thickness

Table 1 Variations in skin friction coefficient and rate of heat transfer for Sakiadis flow at various dimensionless parameters

M	ϕ	Ec	A*	B*	c	$f''(0)$	$-\theta'(0)$
1.0						-1.588128	1.179495
2.0						-1.730070	1.150098
3.0						-1.975926	1.100856
	0.1					-1.426861	1.213765
	0.2					-2.132467	1.489423
	0.3					-3.170742	1.848360
		0.2				-1.426861	1.098226
		0.4				-1.426861	0.867145
		0.6				-1.426861	0.636065
			1			-1.426861	1.118156
			2			-1.426861	1.039048
			3			-1.426861	0.959939
				0.5		-1.426861	1.119728
				1.0		-1.426861	1.023608
				1.5		-1.426861	0.913876
					0.1	-1.426861	1.189354
					0.3	-2.994348	3.034660
					0.5	-4.151636	4.905788

Table 2 Variations in skin friction coefficient and rate of heat transfer for Blasius flow at various dimensionless parameters

M	ϕ	Ec	A*	B*	c	$f''(0)$	$-\theta'(0)$
1.0						0.126476	0.898468
2.0						0.074871	0.876819
3.0						0.029832	0.853217
	0.1					0.227165	0.932990
	0.2					0.177012	1.179995
	0.3					0.165789	1.512313
		0.2				0.227165	0.893418
		0.4				0.227165	0.814273
		0.6				0.227165	0.735129
			1			0.227165	0.806046
			2			0.227165	0.701279
			3			0.227165	0.596512
				0.5		0.227165	0.803410
				1.0		0.227165	0.662989
				1.5		0.227165	0.491699
					0.1	0.227165	0.900338
					0.3	0.454330	1.800676
					0.5	0.601022	2.382071

Table.3 Thermal and physical properties

Properties	Methanol	Cu
$\rho(Kg/m^3)$	792	5180
$C_p(J/Kg.K)$	2545	670
$k\,(W/m.K)$	0.2035	9.7
$\sigma(S/m)$	0.5x10^{-6}	0.74x10^{6}
Pr	7.38	----

Table.4 Validation of the numerical technique

M	*RKS*	*RKF*	*bvp*4*c*	*bvp*5*c*
1	0.898468	0.898468314	0.898468313	0.898468313
2	0.876819	0.876819345	0.876819344	0.876819344
3	0.853217	0.853217871	0.853217870	0.853217870

4. Conclusions

An analysis of the boundary layer of a 2D forced convective flow along a persistent moving horizontal needle in an electrically conducting magneto hydrodynamic dissipative nanofluid was conducted. The energy equation was constructed with the joule heating, viscous dissipation and non-uniform heat source/sink effects. We analyzed the boundary layer behavior of a continuously moving needle in Blasius (moving fluid) and Sakiadis (quiescent fluid) flows. The findings are as follows:

- The boundary layer behaviors of the Sakiadis and Blasius flows are non-uniform.
- The heat transfer rate is high in the Sakiadis flow compared to the Blasius flow.
- The influence of the Lorentz force on the Sakiadis flow is high compared to the Blasius flow.
- Increasing the needle thickness enhances the heat transfer rate of both flows.
- The drag force caused by an external magnetic field reduces the wall friction.

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