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Effects of Heat generation/absorption and thermal radiation on the MHD boundary layer fluid flow along a stretching cylinder embedded in a porous medium

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Abstract: The current work demonstrates the influence of MHD heat transfer characteristics of an incompressible viscous fluid over a continuously expanding horizontal cylinder submerged in a porous material in the presence of internal heat production/absorption, thermal radiation, and the buoyancy force. The partial differential equations that control fluid flow with boundary restrictions were turned into a group of non-linear ODEs with the help of similarity variables, and then they were numerically solved using the bvp approach. The symbolic algebra software Maple has been employed to calculate the numerical components of fluid velocity, temperature, friction factor, and rate of heat transfer. The fluid velocity and heat transfer characteristics for various values of Prandtl number and magnetic parameter are shown in graphs and tables. The primary objective of the current results is to investigate the effects of the magnetic field M, Prandtl number Pr, buoyancy parameter λ, radiation parameter Rd, and heat generation/absorption factor Q on the velocity and temperature gradients along a stretching cylinder. It is anticipated that an upsurge in the porosity factor and the curvature parameter will enhance the temperature gradient in the region of the boundary layer surrounding the cylinder.

Keywords: Buoyancy parameter, Curvature parameter, Heat source/sink, Radiation, Stretching cylinder.

I. INTRODUCTION

A wide range of technical applications have been studied in relation to heat transfer induced by mixed and natural convection in a fluid porous saturated medium, including the petroleum industry, MHD power generators, geothermal systems, plasma research, heat insulation, catalytic reactors, drying technologies, food business, and solar energy collectors. Recent technological advances have made heat transfer around cylinders increasingly popular, especially for electronics chilling, thermal building design, drilling, and geothermal energy generation. Since stretched cylinders and flat plates are widely used in industry, hydrodynamic flow and heat transmission have been widely investigated. The laminar boundary layer flow on a continuous solid surfaces moving in its own plane was first studied by Sakiadis [1][2][3]. Later, Crane [4] extended this study. Wank [5] determined the heat transfer of fluid flow outside of a stretching cylinder. Vajravelu & Rollins [6] analysed the heat transfer characteristics in viscoelastic fluid over a stretching sheet and also for electrically conducting fluid [7]. Ishak et al. [8] investigated the MHD flow and heat transfer outside a stretching cylinder. They also studied the effect of uniform suction/blowing on flow and heat transfer due to a stretching cylinder [9]. Chamkha et al. [10] studied the flow and heat transfer outside a stretching permeable cylinder with thermal stratification and suction/injection effects and obtained the numerical solution for it. Joneidi et al. [11] analysed the MHD flow and heat transfer due to a stretching hollow cylinder.

Wang & Ng [12] studied the slip flow due to a stretching cylinder. Fang et al. [13] analysed the unsteady viscous flow over an expanding stretching cylinder. Mukhopadhyay [14] discussed the chemically reactive solute transfer in a boundary layer slip flow along a stretching cylinder. Gorla et al. [15] investigated the heat transfer of boundary layer flow of nanofluid over a stretching circular cylinder. Lok et al. [16] studied the steady mixed convection flow near an axisymmetric stagnation point on a stretching or shrinking vertical cylinder. Hayat et al. [17] analysed the mixed convection stagnation point flow of an incompressible non-Newtonian fluid over a stretching sheet under convective boundary conditions. Akbar et al. [18] presented the numerical solutions of the steady MHD 2D stagnation point flow of nanofluid over a stretching cylinder under the effects of radiation and convective boundary conditions. Yadav & Sharma [19] analysed the effect of porous medium on MHD fluid flow over a stretching cylinder. Malik et al. [20] studied the effects of variable thermal conductivity and heat generation/absorption on Williamson fluid flow and heat transfer over a stretching cylinder.

Butt et al. [21] numerically investigated the magnetic field effects on entropy generation in viscous flow over a stretching cylinder embedded in a porous medium. Sulochana & Sandeep [22] analysed the stagnation point flow and heat transfer behaviour of nanofluid towards horizontal and exponentially permeable stretching/shrinking cylinders. Qayyum et al. [23] discussed the effect of nonlinear radiation and chemically reactive MHD flow of nanofluid. Alamri et al. [24] studied the effect of mass transfer on MHD second grade fluid towards stretching cylinder by using Catteneo-Christov heat flux model. Hosseinzadeh et al. [25] examined the effect of MHD and thermal radiation on the entropy generation of CNT nanofluids between two stretching rotating discs. Islam et al. [26] analysed the thermal effect for a mixed convection flow of Maxwell nanofluid spinning motion produced by rotating and bidirectional stretching cylinder. Oudina et al. [27] studied the MHD natural convection in an upright porous cylindrical annulus filled with magnetized nanomaterial with discrete heat source.

Abbas et al. [28] discussed the stagnation point flow of hybrid nanofluid with inclined magnetic field over a moving cylinder. Kumar et al. [29] investigated the flow of a ferromagnetic viscous liquid with thermophoretic particle deposition over a stretching cylinder. Hosseinzadeh et al. [30] studied the shape factor effect of mixture fluid suspended by hybrid nanoparticles over vertical cylinder. Wahid et al. [31] analysed the flow and heat transfer of hybrid nanofluid induced by an exponentially stretching/shrinking curved surface. Song et al. [32] investigated the unsteady and incompressible flow of Williamson nano liquid in presence of variable thermal characteristics are persuaded by a permeable stretching cylinder. Many other authors also have studied the flow and heat transfer characteristics of different fluids over a stretching cylinder [33-38]. Reddy et al. [39] discussed the impact of MHD heat transfer properties of an incompressible viscous fluid over a stretching cylinder with heat absorption/generation effect embedded in a porous medium. Bag & Kundu [40] analysed the mass and heat transmission of nano liquid stream over a permeable cylinder accompanied by Catteneo-Christov heat model and thermal radiation with non-linear sort.

In this article, we investigated the flow and heat transmission of an electrically conducting, incompressible fluid over a stretching cylinder in the presence of a magnetic field, a heat source, and a heat sink. By using similarity transformations to reduce the number of independent variables, the non-linear coupled partial differential governing equations were converted into a system of coupled ordinary differential equations. Then, graphs and tables were used to illustrate the findings.

II. MATHEMATICAL FORMULATION

Consider the flow of a two dimensional electrically conducting Newtonian fluid caused by free convection from a horizontal cylinder with radius $'a'$ in the presence of both thermal radiation and buoyancy force while immersed in a porous medium as shown in the fig 1.

To idealize the considered model, we have assumed that an axial overextension of the cylinder is intended with a linear velocity $u_w(x) = U\frac{x}{l}$,, and a thermal change $T_w(x) = T_\infty + T_0\left(\frac{x}{l}\right)^n$ is expected to occur at the surface of the cylinder. On the cylinder, the x −axis is measured parallel to its axis, while the r −axis is measured radially. A radial homogeneous magnetic field with intensity B_0 is applied and there is no consideration of viscous dissipation in the energy equation. In comparison with the applied magnetic field, the resultant magnetic field is ignored. Also, we assumed that, λ should be of an order greater than one because the flow is caused by free convection and buoyancy forces should therefore be dominant.

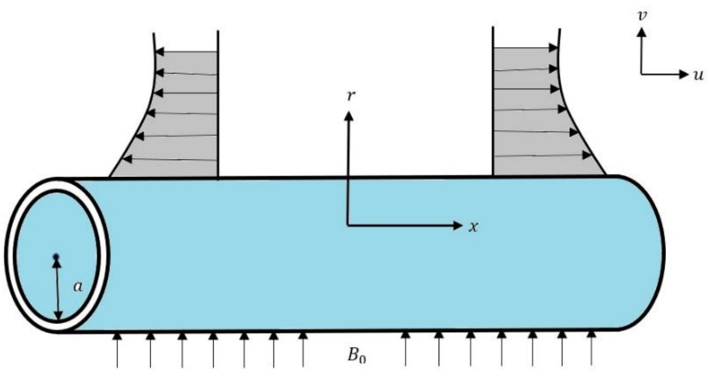

Fig 1: Diagrammatic representation of flow regime

Implementation of boundary layer approximation results in the following governing equations

Continuity Equation:

$$\frac{\partial(ru)}{\partial x} + \frac{\partial(rv)}{\partial r} = 0, \quad (1)$$

Momentum Equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=\frac{\nu}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)-\frac{\sigma B_0^2}{\rho}u-\frac{\nu}{k_p}u+g\beta_T(T-T_\infty), \quad (2)$$

Energy Equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial r}=\frac{1}{\rho C_p}\left[\frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right]+\frac{Q_0}{\rho C_p}(T-T_\infty)-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial r}. \quad (3)$$

Subjected to the boundary conditions

$$u=u_w(x)=U\frac{x}{l}, v=0, T=T_w(x)=T_\infty+T_0\left(\frac{x}{l}\right)^n \text{ at } r=a, \quad (4)$$

$$u\to 0, T\to\infty \text{ as } r\to\infty. \quad (5)$$

Where the parameters are as defined in the nomenclature.

To transform the system of eqns. (1)-(5) into dimensionless form, we introduce the dimensionless similarity variables as,

$$\eta=\frac{r^2-a^2}{2a}\left(\frac{u_w}{\nu x}\right)^{\frac{1}{2}}, \qquad \psi=(\nu x u_w)^{\frac{1}{2}}a\,f(\eta),$$

$$u=\frac{1}{r}\frac{\partial\psi}{\partial r}, \qquad v=-\frac{1}{r}\frac{\partial\psi}{\partial x}, \qquad \theta=\frac{T-T_\infty}{T_w-T_\infty}. \quad (6)$$

And using the Roseland approximation of thermal radiation, we get

$$q_r=-\frac{16\sigma^* T_\infty^3}{3k^*}\frac{\partial T}{\partial r} \quad (7)$$

Then, we have

$$(1+2\eta\beta)f'''+ff''+2\beta f''-(f')^2-(M+K)f'+\lambda\theta=0, (8)$$

$$(1+2\eta\beta)\left(1+\frac{4}{3}Rd\right)\theta''+2\beta\left(1+\frac{2}{3}Rd\right)\theta'+\Pr(f\theta'-nf'\theta)-\Pr Q\,\theta=0. \quad (9)$$

The boundary constraints (5) will become,

$$f(0)=0, f'(0)=1, \theta(0)=1, f'(\infty)\to 0, \theta(\infty)\to 0. (10)$$

Where the prime indicates differentiation with respect to η, ψ is the stream function, $\beta=\left(\frac{\nu l}{a^2 U}\right)^2$ is the curvature parameter, $M=\frac{\sigma B_0 l}{\rho U}$ is the magnetic parameter, $K=\frac{\nu l}{U k_p}$ is the permeability parameter, $Q=\frac{Q_0 l}{U\rho C_p}$ is the heat generation/absorption parameter, $Pr=\frac{\nu}{\alpha}$ is the Prandtl number, $\lambda=\frac{Gr_x}{Re^2}$ is the buoyancy parameter where $Gr_x=\frac{g\beta_T(T_w-T_\infty)x^3}{\nu^2}$ is the local Grashof number and $Re=\frac{u_w x}{\nu}$ is the local Reynold's number and $Rd=\frac{4\sigma^* T_\infty^3}{kk^*}$ is the radiation parameter and n is the surface temperature exponent.

Skin friction coefficient:

The shearing stress at the surface is given by,

$$\tau_w=\mu\left(\frac{\partial u}{\partial r}\right)_{r=a} \quad (11)$$

Where μ is the coefficient of viscosity.

The skin friction coefficient at the surface is given by,

$$C_f=\frac{2\tau_w}{\rho u_w^2}$$

$$\Rightarrow \quad \frac{1}{2}C_f Re^{\frac{1}{2}}=f''(0). \quad (12)$$

Heat transfer coefficient:

The rate of heat transfer at the surface is given by,

$$q_w=-k\left(\frac{\partial T}{\partial r}\right)_{r=a} \quad (13)$$

The Nusselt number is defined as,

$$Nu_x = \frac{xq_w}{k\,(T_w - T_\infty)}$$

$$\Rightarrow \quad Nu\, Re^{\frac{1}{2}} = -\theta'(0). \tag{14}$$

Where $Re = \frac{u_w x}{\nu}$ is the local Reynolds number.

The symbolic algebra software Maple is used to numerically answer the governing non-linear boundary layer equations using the bvp method. Graphs are used to display how different physical factors affect the velocity and temperature profiles. For various values of physical parameters, the numerical values of skin friction and heat transfer coefficient are calculated and displayed in tables.

III. FIGURES AND TABLES

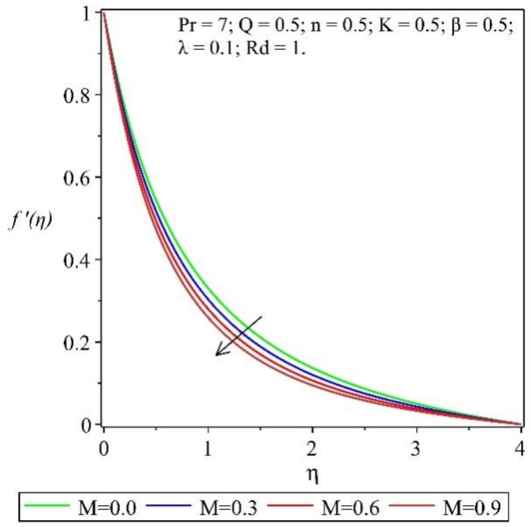

Fig 1: Velocity Profile vs Magnetic Parameter

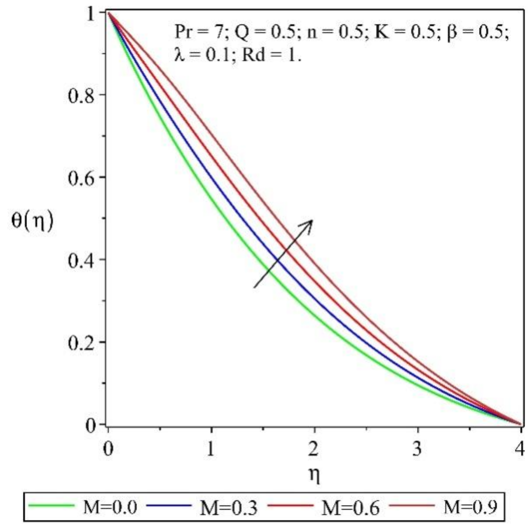

Fig 2: Thermal Profile vs Magnetic Parameter

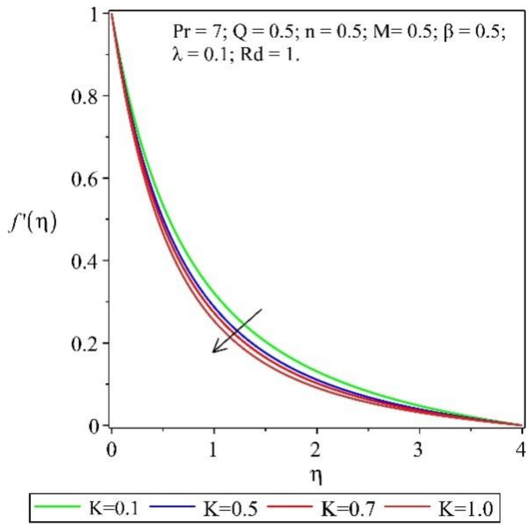

Fig 3: Velocity Profile vs Permeability Parameter

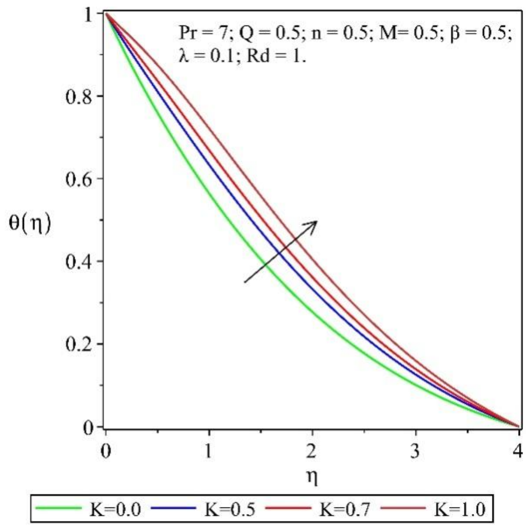

Fig 4: Thermal Profile vs Permeability Parameter

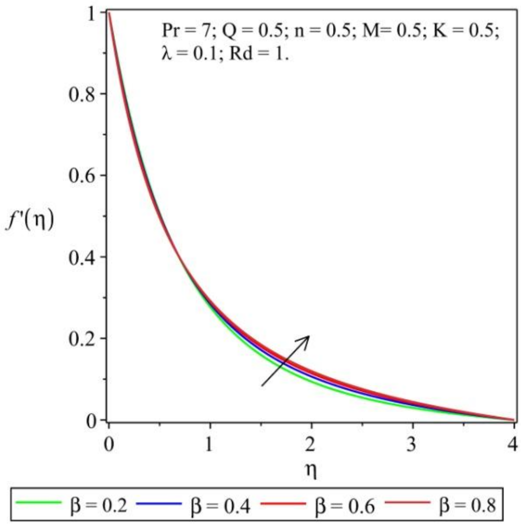

Fig 5: Velocity Profile vs Curvature Parameter

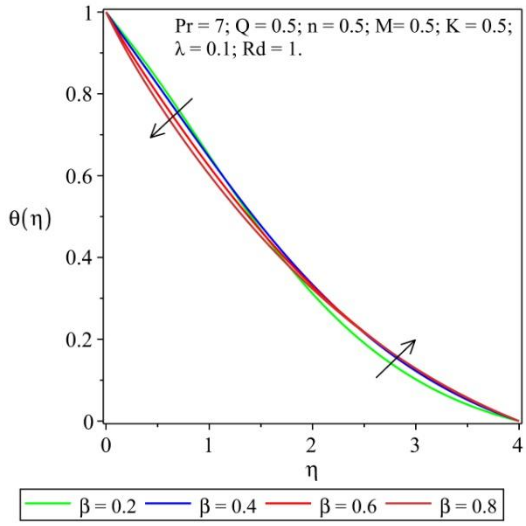

Fig 6: Thermal Profile vs Curvature Parameter

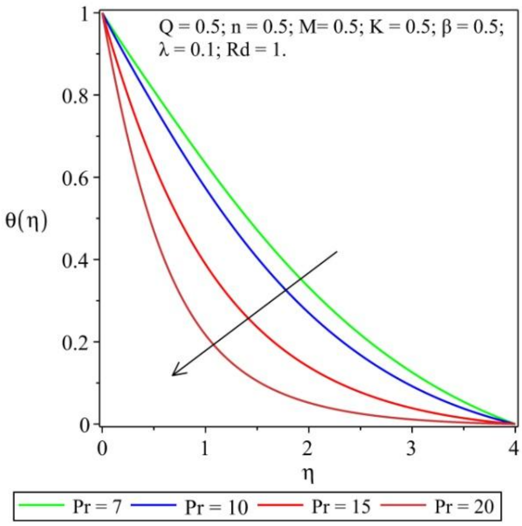

Fig 7: Thermal Profile vs Prandtl Number

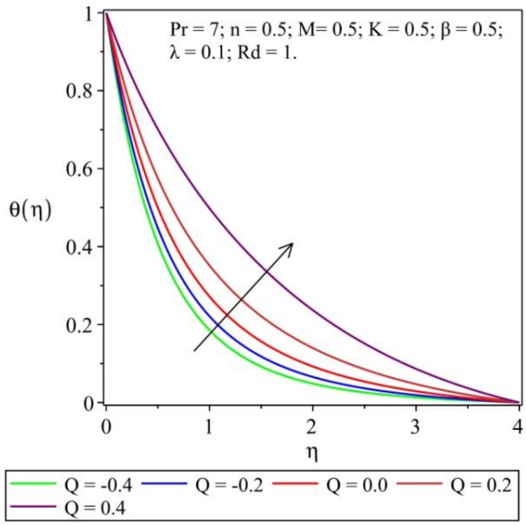

Fig 8: Thermal Profile vs Heat source/sink Parameter

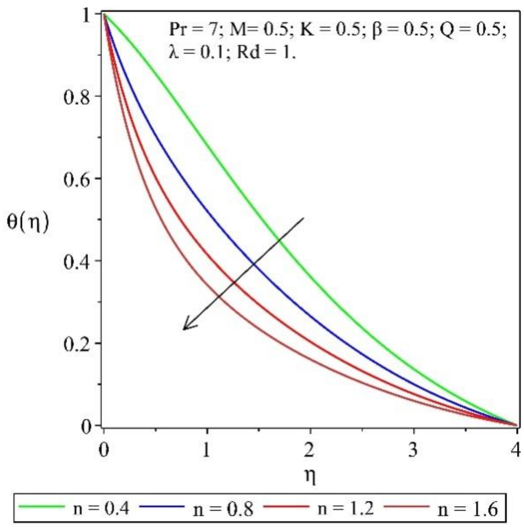

Fig 9: Thermal Profile vs surface temperature exponent

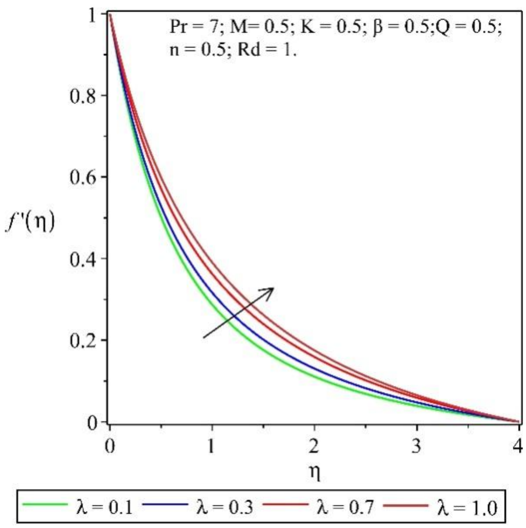

Fig 10: Velocity Profile vs buoyancy parameter

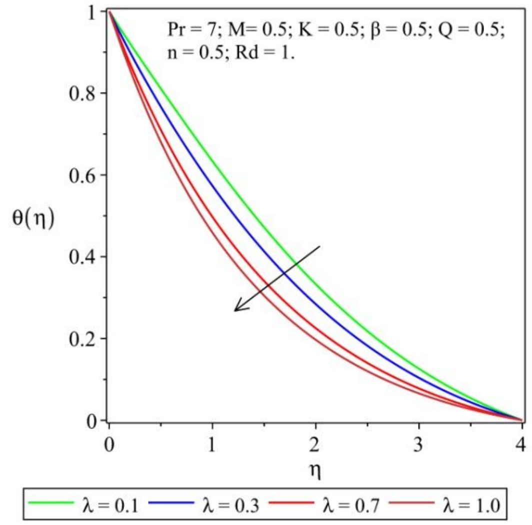

Fig 11: Thermal Profile vs buoyancy parameter

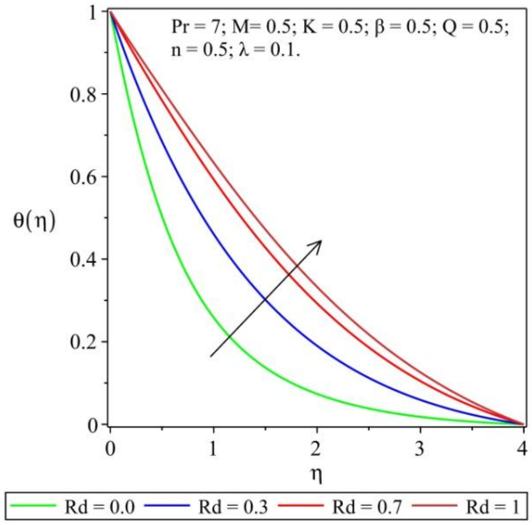

Fig 12: Thermal Profile vs Radiation parameter

Table 1: Comparison of $-f''(0)$ for various values of M when $K = Q = \beta = n = Rd = \lambda = 0$.

M	Reddy et al. [39]	Present results
0	0.9999498	1.0000000
0.2	1.09544512	1.09544511

Table 2: Comparison of $-\theta'(0)$ for various values of Pr and n when $K = Q = \beta = Rd = \lambda = 0$.

Pr	n	Reddy et. al [39]	Present study
0.72	1	0.80868054	0.80863134
1	1	1.00000117	1.00000000
3	-1	0.00000137	0.00000043
3	0	1.16525326	1.16524595
3	1	1.92367744	1.92368261
3	2	2.50970910	2.50972523
10	-1	-0.25924948	-0.23104096
10	0	2.30801969	2.30800133
10	1	3.72059137	3.72067116
10	2	4.79674206	4.79687061

Table 3: Numerical computations of skin friction $-f''(0)$ and the Nusselt number $-\theta'(0)$ for several quantities of physical factors.

Pr	Q	n	K	M	β	Rd	λ	$-f''(0)$	$-\theta'(0)$
7 10 15	0.5	0.5	0.5	0.5	0.5	1	0.1	1.577611 1.580765 1.590339	0.413128 0.497662 0.886452
7	-0.2 0 0.2	0.5	0.5	0.5	0.5	1	0.1	1.600176 1.597211 1.592745	1.714773 1.482805 1.187743
7	0.5	0.4 0.8 1.6	0.5	0.5	0.5	1	0.1	1.574999 1.583910 1.594288	0.248972 0.831155 1.629815
7	0.5	0.5	0 0.5 1	0.5	0.5	1	0.1	1.387963 1.577611 1.746441	0.583577 0.413128 0.243488
7	0.5	0.5	0.5	0 0.3 0.6	0.5	1	0.1	1.387963 1.504612 1.612848	0.583577 0.481246 0.379116
7	0.5	0.5	0.5	0.5	0.2	1	0.1	1.447349	0.320249

					0.4 0.6			1.534289 1.620600	0.373172 0.453139
7	0.5	0.5	0.5	0.5	0.5	0 0.5 1	0.1	1.597474 1.582394 1.577611	1.324095 0.576973 0.413128
7	0.5	0.5	0.5	0.5	0.5	1	0.1 0.6 1	1.577611 1.339742 1.174310	0.413128 0.650072 0.761279

IV. CONCLUSION

The impact of MHD heat transfer boundary layer flow over a continuously expanding horizontal cylinder submerged in a porous medium is investigated numerically in the presence of a heat source/sink, radiation, and the buoyancy force. Similarity variables are used to convert PDEs into ODEs. To get the desired outcomes, the bvp approach is applied. Discussion of the diagrammatic portrayal of the impact of many significant flow parameters on velocity and thermal profiles. The numerical results were observed to be in good correlation with Reddy et al. [39]'s findings. The research mainly focuses on the influence of the stretching cylinder's curvature parameter, which is a significant factor affecting both fluid velocity and temperature parameters.

- As the parameters M and K increase, the velocity profile diminishes, and the thermal gradient increases.
- As the factors β, Q and Rd increases, the thickness of the thermal boundary layer enhances.
- A higher β and λ results in a higher velocity.
- The temperature profile decreases with an increase in Pr, n and λ.
- With increasing values of M, K and β, the skin friction coefficient increases, but diminishes with increasing λ values.
- In contrast, Nusselt number decreases with increasing values of M, K, Q & Rd while increases with the increasing values of β, Pr, n & λ.

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NOMENCLATURE:

a	radius of the cylinder	T_0	reference temperature of the fluid
B_0	magnetic field	T_∞	fluid temperature in free stream
C_p	specific heat at constant pressure	T_w	variable temperature
f'	first derivative w.r.to η	u_w	velocity along axial direction
f''	second derivative w.r.to η	u	velocity component along x −direction
f'''	third derivative w.r.to η	v	velocity component along r −direction
g	gravitational field	U	reference velocity
k_p	permeability of the porous medium	α	thermal diffusivity
k	thermal conductivity	β	curvature parameter
k^*	Stefan-Boltzmann constant	β_T	thermal expansion coefficient
K	permeability parameter	η	similarity variable
l	characteristic length	θ	dimensionless temperature
M	magnetic parameter	θ'	first derivative w.r.to η
n	exponent of the surface temperature	θ''	second derivative w.r.to η
Pr	Prandtl number	λ	buoyancy parameter
Q	heat generation/absorption parameter	ν	kinematic viscosity
Q_0	volumetric rate of heat source/sink	ρ	density of the fluid
Rd	Radiation parameter	σ	electrical conductivity
T	fluid temperature	ψ	stream function