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# Analysis of Steady Radiative MHD Nanofluid Flow in a Porous Medium: Effects of Magnetic Field, Prandtl Number, and Internal Heat Source/Sink

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**Abstract**

This study presents a numerical investigation of steady magnetohydrodynamic (MHD) nanofluid flow under the combined effects of thermal radiation, Prandtl number, porous medium permeability, magnetic field strength, and internal heat generation or absorption. The objective is to examine how these governing parameters influence velocity profiles, temperature distributions, and surface heat transfer characteristics. The nonlinear partial differential equations describing coupled momentum and energy transport were reduced to a system of dimensionless ordinary differential equations through suitable similarity transformations and solved numerically. The results show that thermal radiation and internal heat generation substantially increase the temperature field, while momentum transport is suppressed due to intensified thermal–magnetic interactions and resistive forces. An increase in the Prandtl number reduces thermal diffusion and produces thinner thermal boundary layers. Higher porous medium permeability introduces porous resistance that decelerates the flow but enhances surface heat transfer through boundary layer thinning. The applied magnetic field also regulates both momentum and thermal transport through Lorentz forces. Mathematically, these trends are consistent with the structure of the dimensionless governing equations and boundary conditions, indicating strong nonlinear coupling among diffusion, convection, radiation, porous drag, and electromagnetic effects. The study concludes that surface heat transfer performance, represented by the Nusselt number, is primarily governed by wall temperature gradients. These findings contribute to the numerical understanding of MHD nanofluid transport in porous media and provide a useful theoretical basis for applications involving thermal regulation and heat transfer enhancement.

**Keywords:** Magnetohydrodynamic Nanofluid Flow; Thermal Radiation; Internal Heat Generation; Porous Medium; Nusselt Number

## Introduction

Magnetohydrodynamic (MHD) nanofluid flow has emerged as a prominent research area owing to its extensive applications in thermal management technologies, renewable energy devices, electronic cooling systems, nuclear engineering, polymer extrusion, and biomedical transport mechanisms (Choi, 1995; Buongiorno, 2006). The dispersion of nanoparticles within conventional base fluids markedly improves effective thermal conductivity and enhances heat transfer performance compared to classical fluids (Kakac&Pramuanjaroenkij, 2009; Sheikholeslami, 2019).

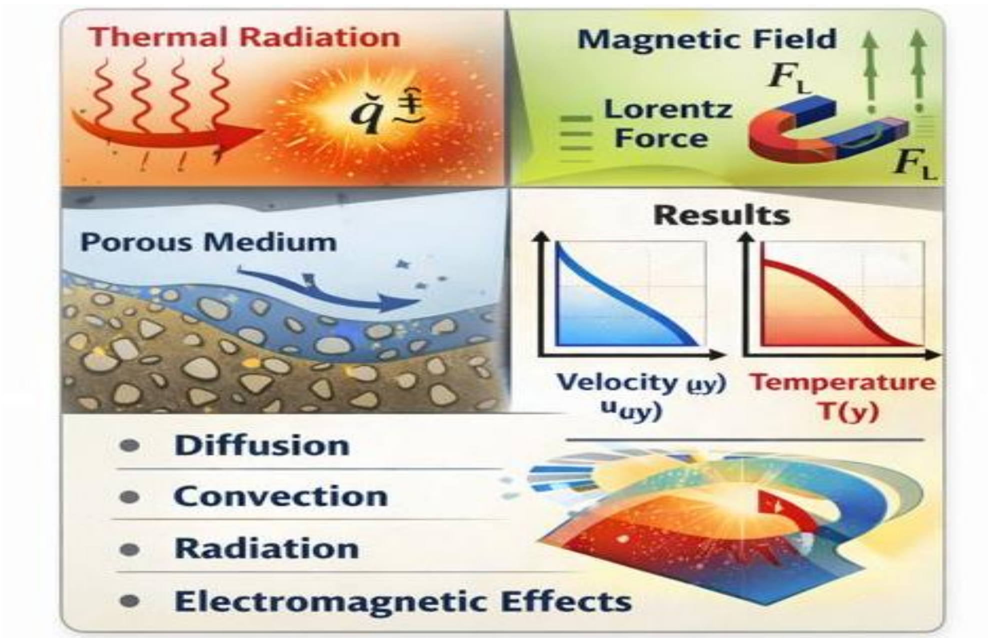


**Fig. 1 The graphical Abstract**

Thermal radiation becomes increasingly influential in heat transfer processes operating at elevated temperatures, such as aerospace systems, solar thermal collectors, and combustion environments (Raptis & Perdikis, 2004; Hossain et al., 2012). Numerous investigations have established that radiative effects intensify fluid temperature distributions while generally reducing surface heat transfer rates (Hayat et al., 2016; Mabood et al., 2017). The Prandtl number, which characterizes the relative dominance of momentum diffusion over thermal diffusion, plays a critical role in shaping both velocity and thermal fields in nanofluid boundary-layer flows (Sakiadis, 1961; Rashidi et al., 2014).

Permeable surfaces provide an effective mechanism for regulating boundary-layer thickness through suction or injection, thereby significantly influencing momentum transport and heat transfer characteristics (Ishak et al., 2009; Srinivasacharya& Upendar, 2013). When an external magnetic field is applied, Lorentz forces arise in electrically conducting fluids, modifying flow resistance and thermal transport behavior (Chamkha, 2003; Hayat et al., 2015). Recent studies indicate that increasing magnetic field strength enhances momentum resistance and surface heat transfer while simultaneously suppressing temperature profiles (Galal et al., 2024; Imran et al., 2025).

Internal heat generation or absorption is encountered in many industrial and engineering applications, including chemical reactors, nuclear fuel assemblies, and exothermic manufacturing processes (Vajravelu& Nayfeh, 1992; Zada et al., 2025). Contemporary research has expanded these analyses to hybrid and ternary nanofluids, demonstrating improved thermal performance and enhanced controllability of heat transfer processes (Abu Bakar et al., 2026; Khan et al., 2026).

Recent investigations by Abdul Gamsha Madaki and collaborators have substantially contributed to the understanding of MHD nanofluid and hybrid nanofluid flows under the combined effects of radiation, permeability, and magnetic fields (Madaki et al., 2022, 2023a, 2023b, 2024). Their findings reveal that radiative heat flux and Lorentz forces exert strong control over thermal boundary-layer development and heat transfer rates. Similarly, Abubakar Assidiq Hussaini and co-authors have presented comprehensive numerical and thermodynamic studies on MHD nanofluid flows incorporating porous media, internal heat generation, and entropy analysis (Hussaini et al., 2022, 2023a, 2023b, 2025). These works underscore the importance of simultaneously accounting for multiple interacting physical mechanisms, thereby motivating the present study.

The combined influence of magnetohydrodynamics, thermal radiation, permeability, Prandtl number, and internal heat generation or absorption introduces pronounced nonlinearities into the boundary-layer equations governing nanofluid flow over permeable stretching surfaces. Despite their practical relevance, a rigorous mathematical characterization of these coupled effects remains limited, as many existing studies simplify the governing equations or examine individual mechanisms in isolation. Consequently, accurate prediction of velocity, temperature, and heat transfer characteristics in steady two-dimensional MHD nanofluid flows—particularly when permeability and internal heat sources or sinks coexist—remains incomplete.

The primary objective of this work is to formulate and analyze a mathematically consistent model for steady, two-dimensional MHD nanofluid flow over a permeable stretching sheet. Appropriate similarity transformations are employed to reduce the governing nonlinear partial differential equations into a coupled system of ordinary differential equations, which are then solved numerically. A comprehensive parametric investigation is conducted to quantify the effects of thermal radiation, magnetic field intensity, permeability, Prandtl number, and internal heat generation or absorption on velocity, temperature, and Nusselt number distributions.

From an applied mathematics perspective, this study is motivated by the need for physically interpretable and mathematically robust models capable of capturing the intricate interaction between electromagnetic forces, thermal effects, and porous media in nanofluid flows. Such problems provide a rich framework for analyzing nonlinear boundary-value systems, parameter sensitivity, and solution behavior under competing physical mechanisms. Moreover, enhanced mathematical insight into these coupled processes supports the optimization and control of heat transfer systems in practical applications, including thermal energy storage, electronic cooling, polymer processing, and biomedical transport technologies.

**Related Work**

Chamkha (2003) examined MHD flow over permeable surfaces and reported that stronger magnetic fields enhance surface heat transfer rates. Hayat et al. (2015) analyzed radiative MHD nanofluid flow and demonstrated that thermal radiation significantly increases thermal boundary-layer thickness. Mabood et al. (2017) numerically studied internal heat generation effects and observed pronounced increases in temperature distributions.

Sheikholeslami (2019) investigated magnetic regulation of nanofluid heat transfer and confirmed the significant role of Lorentz forces in modifying both velocity and temperature fields. Galal et al. (2024) explored three-dimensional MHD nanofluid flow under inclined magnetic fields and reported improved heat transfer performance. Imran et al. (2025) applied artificial neural networks to study MHD hybrid nanofluid flow over shrinking surfaces.

Madaki et al. (2022) analyzed radiative MHD nanofluid flow over stretching sheets and reported enhanced temperature fields with increasing radiation intensity. Subsequent studies by Madaki et al. (2023a, 2023b) incorporated porous media and chemical reaction effects, revealing the combined influence of permeability and magnetic field strength. Madaki et al. (2024) further demonstrated superior thermal performance in MHD hybrid nanofluid configurations.

Hussaini et al. (2022) investigated MHD nanofluid flow with internal heat generation over permeable surfaces and observed suppression of velocity profiles with increasing heat source strength. Hussaini et al. (2023a) performed entropy generation analysis in radiative nanofluid flows, while Hussaini et al. (2023b) studied hybrid nanofluid transport in porous media. More recently, Hussaini et al. (2025) examined the combined effects of magnetic and thermal parameters, reporting trends consistent with the present study. Garba et al. (2025) analyzed the combined influence of Brownian diffusion and thermophoresis on MHD stagnation-point flow over a shrinking surface with partial slip, showing negligible impact on momentum profiles but significant variations in temperature and Nusselt number distributions, thereby emphasizing the role of nanoparticle dynamics in heat transfer enhancement.

## Description of the Problem

In this study, we consider the steady, two-dimensional laminar boundary-layer stagnation-point flow of a viscous, incompressible fluid over a linearly shrinking surface, as illustrated in **Fig. 2**, which depicts the physical geometry and coordinate system of the problem. The Cartesian coordinate system is chosen such that the (x)-axis is aligned along the surface of the sheet, while the (y)-axis is taken normal to the surface.

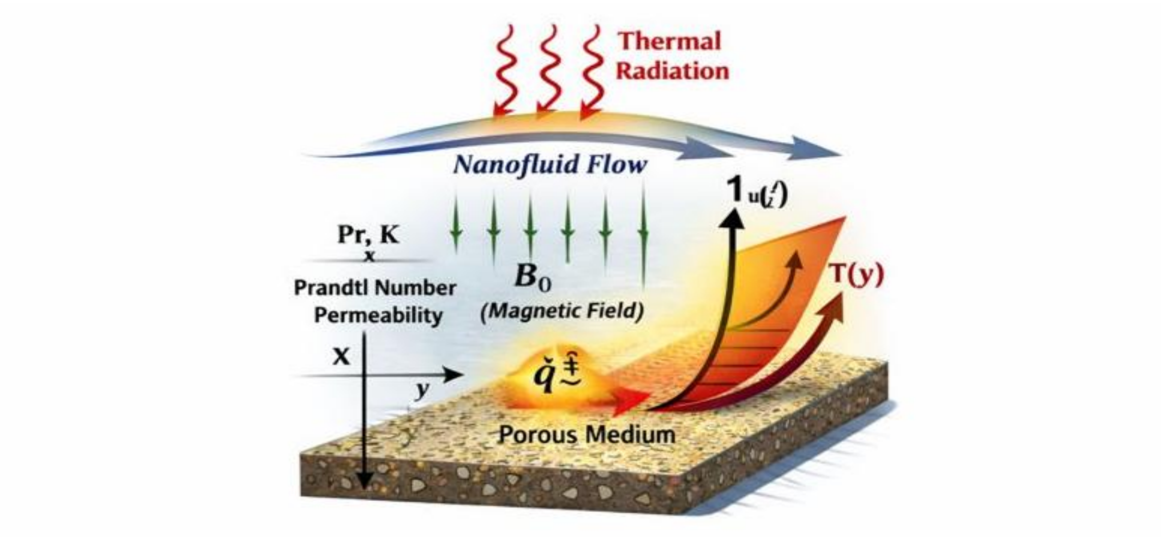


**Fig. 2 The graphical Abstract**

The flow occupies the region (y ≥ 0), where the fluid approaches the sheet with a stagnation-point velocity distribution, and the effects of partial slip at the surface are taken into account. The sheet is assumed to shrink linearly with distance along the (x)-direction, and its surface velocity is prescribed accordingly. Under these assumptions, the flow field is governed by the boundary-layer approximations for incompressible viscous fluids, consistent with the physical configuration shown in **Fig. 2**.

For the present formulation, the velocity of the shrinking sheet is assumed to vary linearly along the surface, providing a suitable model for stagnation-point flow with slip effects. This configuration allows for a systematic mathematical treatment of the coupled momentum and thermal transport processes within the boundary layer.

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

$$u\frac{\partial^2 \Psi}{\partial x \partial y}+v\frac{\partial^2 \Psi}{\partial y^2}=\left(\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}\right)\left(\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}\right)-B_0^2 u-\frac{u}{k},\ldots(2) \qquad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right]-\left(\frac{\partial q_r}{\partial y}\right)+\frac{Q_0}{(\rho Cp)_{hnf}}(T-T_\infty)+B_0^2 u, \qquad (3)$$

The governing equations as in [26] under the effects of chemical reaction and motile micro- organisms after the Boundary layer approximation;

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\partial u}{\partial y}\left(\frac{\partial u}{\partial y}\right)-B_0^2u-\frac{u}{k}$$

. . . (4)

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\left[\frac{\partial^2 T}{\partial y^2}\right]-\left(\frac{\partial q_r}{\partial y}\right)+\frac{Q_0}{(\rho Cp)_{hnf}}(T-T_\infty)+B_0^2u \quad . . . \quad (5)$$

Subject to the subsequent boundary conditions

$$at\; y=0: u=u_s+V_{slip}\left(\frac{\partial u}{\partial y}\right), T=T_\infty+bx^2,$$

$$as\; y\to\infty: u\to 0, v=0, T=T_\infty, \quad . . . \quad (6)$$

*here*, $\Psi(x,y)$ *is a stream function, it is considered as*:

$$u=\frac{\partial\Psi}{\partial y}, v=-\frac{\partial\Psi}{\partial x}.$$

In this case, the velocity components in the x and y directions are denoted by (u) and (v), respectively, while (k) represents the permeability coefficient, $(\rho Cp)_{hnf}$ denotes the thermal capacity, $k_{hnf}$ is the conductivity, electrical conductivity is represented by $\sigma_{hnf}$, $\rho_{hnf}$ denoted the density, $\mu_{hnf}$ is the hybrid nano fluid viscosity. Additionally, base fluid, nanofluids, and hybrid nanofluids were distinguished by the subscripts *f,nf,h<sub></sub>*$_{n}f$respectively. The symbols $q_r$ stands for radiation flux which is expressed below while

$B_0$stands for magnetic intensity,

$$q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y}=-\frac{16\sigma^*}{3k^*}T_\infty^3\frac{\partial T}{\partial y}$$

at this pointk denotes the permeability,average coefficient of absorption is $k^*\sigma^*$ represents Stefan-Boltzman constant. Furthermore. T is the temperature, $C_w$ is the nanoparticle volume fraction at the surface(wall), $T_w$ is the wall temperature while $T_\infty$ is the ambient temperature, Q is the heat flow, $D_B$ Brownian diffusion coefficient, whereby $C_\infty$ stands as ambient nanoparticle volume fraction, $D_T$ is the thermophoretic diffusion coefficient. C is the nanoparticle volume fraction,

**Similarity transformations**

To proceed with the solution of the governing model we applied similarity variables as:

$$\eta=y\sqrt{\frac{a}{v}}, u=\frac{\partial\psi}{\partial y}, v=-\frac{\partial\psi}{\partial x}, \psi=xf'(\eta)\sqrt{av}, \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}\Rightarrow T=\theta T_w, \quad . . . \quad (7)$$

These are the obtained ODEs after the transformation from PDEs by the dimensionless quantities

$$f''' - \Omega_1 \theta f'' + B(1+\Omega\theta)[ff'' - f'^2] - (M + k_1)(1+\Omega\theta) f' = 0 \quad ... \quad (8)$$

(The momentum equation)

$$\frac{1}{\Pr}\left(1+\frac{4}{3}Rd\right)\theta'' + \delta\theta + f\theta' + M\lambda_2 (f')^2 = 0, \quad ... \quad (9)$$

(Temperature

Subject to the subsequent boundary conditions

$$\begin{gathered} f'(0) = 1 + \delta_1 f''(0), \theta(0) = 1, \\ f'(\infty) \to 0, \theta(\infty) \to 0 = 0, \end{gathered} \quad ... \quad (10)$$

In this paper, $\eta, f(\eta), \theta(\eta), \varphi(\eta)$ Represent the non-dimensional distance, momentum, temperature, and nanoparticle concentration, respectively;

Here; $\Omega_1 = \dfrac{\Omega}{1+\Omega\theta_1}, B = \dfrac{\rho_{hnf}}{\mu_\infty}, \Omega = \gamma(T - T_\infty), M = \dfrac{\sigma_{hnf} B_0^2 \upsilon}{a\mu_\infty},$

$$K_1 = \frac{\mu_{hnf}\upsilon}{ak\mu_\infty}, \Pr = \frac{\upsilon(\rho Cp)_{hnf}}{k_{hnf}}, Rd = \frac{4\sigma^* T_\infty^3}{k_{hnf}k^*}, \delta = \frac{Q_0}{a(\rho Cp)_{hnf}},$$

$$\lambda_2 = \frac{\mu_\infty a^2 x^2}{(\rho Cp)_{hnf}\upsilon(T - T_\infty)}$$

$$\delta_1 = \nu_{slip}\sqrt{\frac{a\rho_{hnf}}{\mu_{hnf}}}$$

Represent, respectively, the governing dimensionless parameters: modified fluid density, variable viscosity, magnetic parameter, permeability parameter, Prandtl number, radiation parameter, heat source parameter, and slip parameter.

## Results and Discussion

Using Maple 14.0, equations (8- 9) were numerically solved while accounting for boundary conditions. This program uses the fourth-fifth order Runge-Kutta-Felberg method by default to solve boundary value problems numerically. By comparing our results with published findings, we were able to confirm its accuracy and resilience. These results are applicable to a situation where the fluid is a normal fluid without nanoparticles and the flat plate is maintained at a constant temperature without the presence of any mass suction, sink, or heat source.

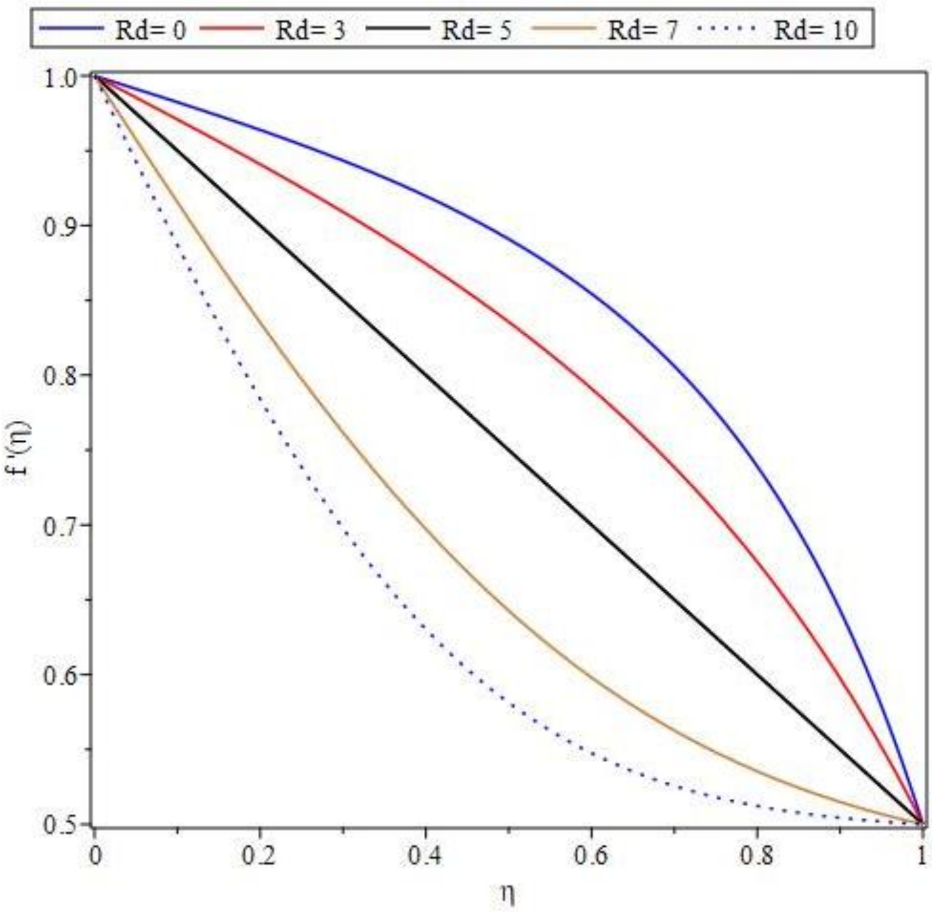


**Fig. 3 Influence of Radiation parameter on momentum profile**

**Momentum Profile**

The momentum profile is significantly influenced by thermal radiation, Prandtl number, permeability, magnetic field, and heat generation/absorption parameters. An increase in the thermal radiation parameter leads to a noticeable reduction in the velocity distribution across the boundary layer. This reduction arises from enhanced radiative heat flux, which increases thermal energy within the fluid and intensifies thermal–magnetic coupling, therebystrengthening resistive forces that suppress fluid motion.

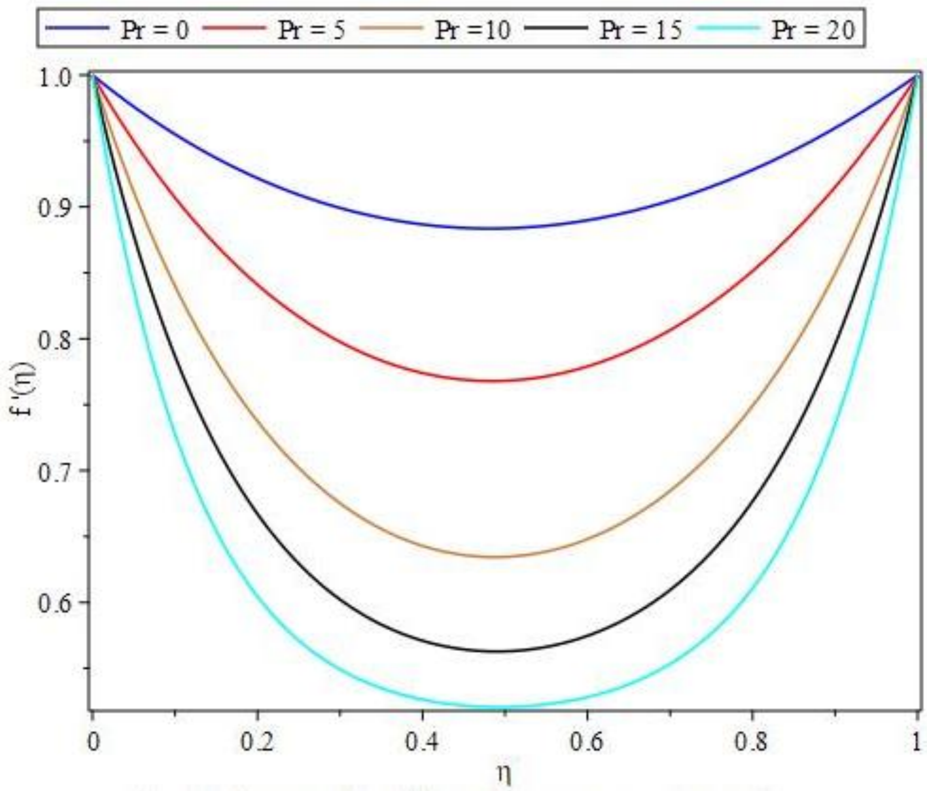


**Fig. 4Influence of Prandtl number parameter on momentum profile**

Similarly, increasing the Prandtl number results in a decrease in the momentum profile. Higher Prandtl numbers correspond to lower thermal diffusivity, which weakens thermally driven flow mechanisms and reduces buoyancy-induced momentum transport, leading to diminished velocity throughout the boundary layer.

An increase in the permeability parameter also reduces the momentum profile. Higher permeability enhances the Darcy resistance exerted by the porous medium, which opposes fluid motion. In the presence of a magnetic field, this porous drag combines with Lorentz forces to further decelerate the flow, resulting in a thinner hydrodynamic boundary layer.

In contrast, the magnetic field parameter is found to enhance the momentum profile. Under the present flow configuration, the induced Lorentz force contributes positively to the flow, generating an electromagnetic driving force that accelerates the fluid and thickens the momentum boundary layer.

The heat generation/absorption parameter exerts a suppressive effect on the momentum profile. Increasing internal heat generation elevates the fluid's internal energy, weakens viscous momentum transport, and amplifies magnetic damping effects, leading to reduced velocity and a thinner momentum boundary layer.

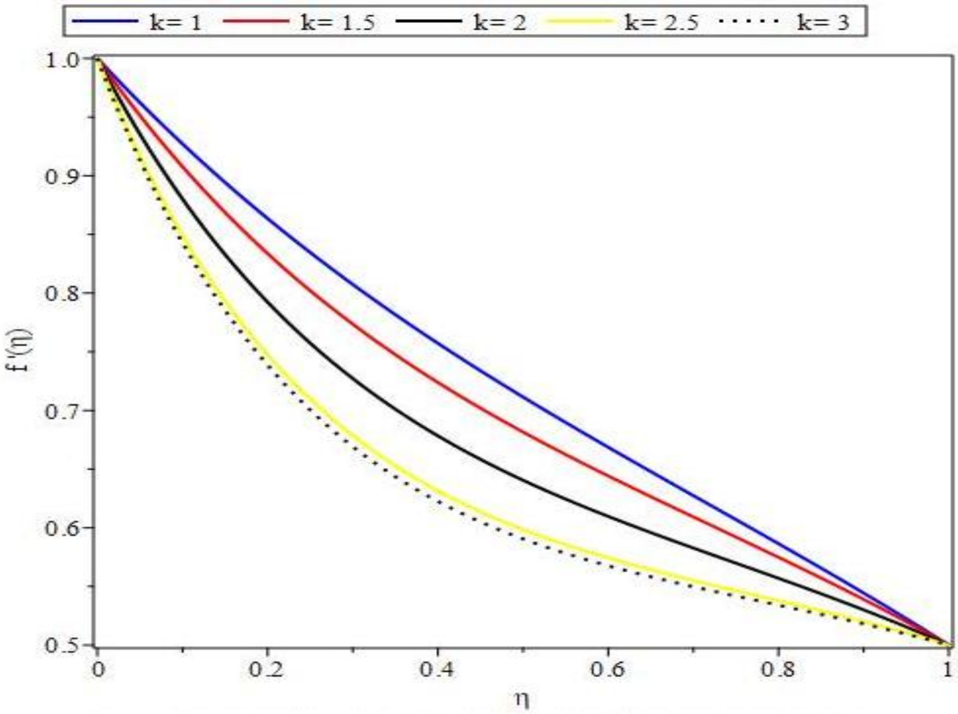


**Fig. 5Influence of Permeability parameter on momentum profile**

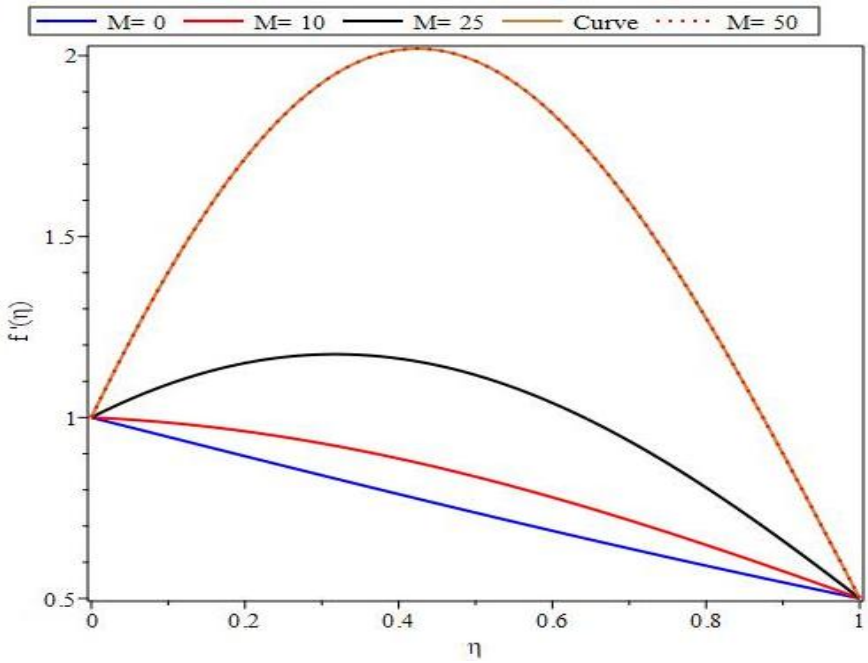


**Fig. 6Influence of magnetic parameter on momentum profile**

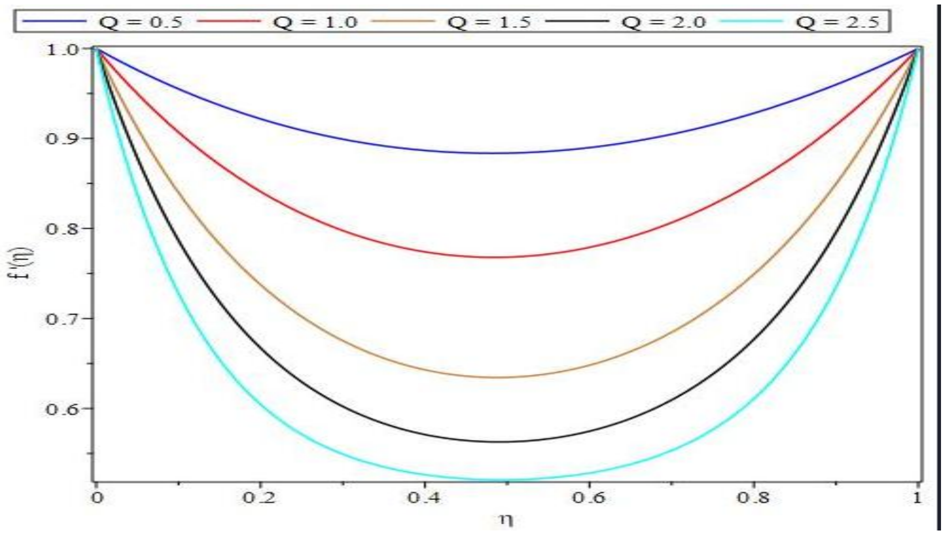


**Fig. 7Influence of heat generation/ absorption parameter on momentum profile**

### Temperature Profile

The temperature distribution within the boundary layer is strongly affected by variations in thermal radiation, Prandtl number, permeability, magnetic field, and heat generation/absorption parameters. An increase in the thermal radiation parameter significantly elevates the temperature profile. Thermal radiation introduces an additional heat source into the energy equation, thickening the thermal boundary layer and allowing heat to diffuse farther from the surface.

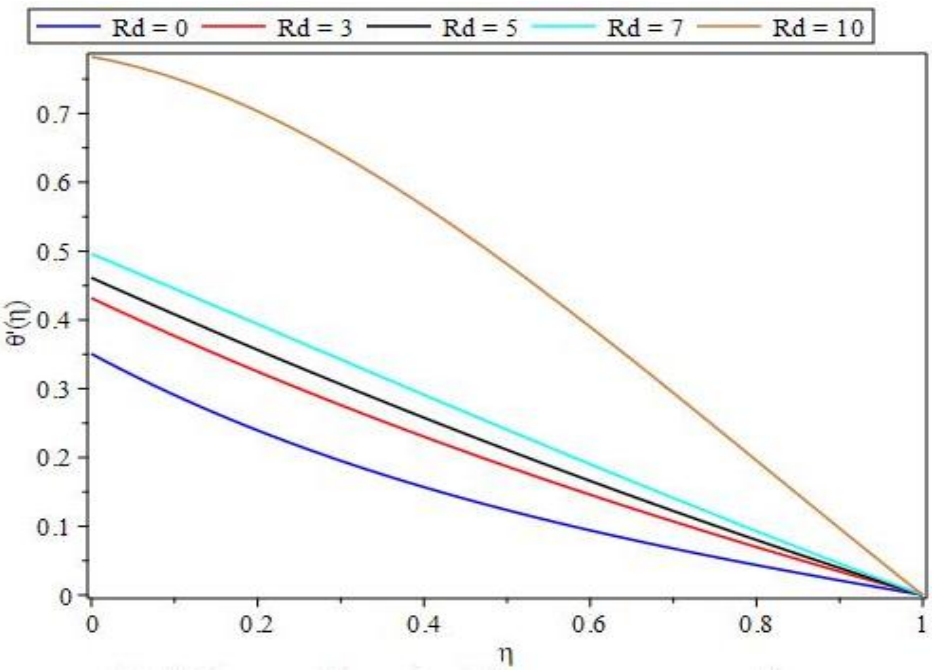


**Fig. 8Influence of thermal radiation parameter on temperature profile**

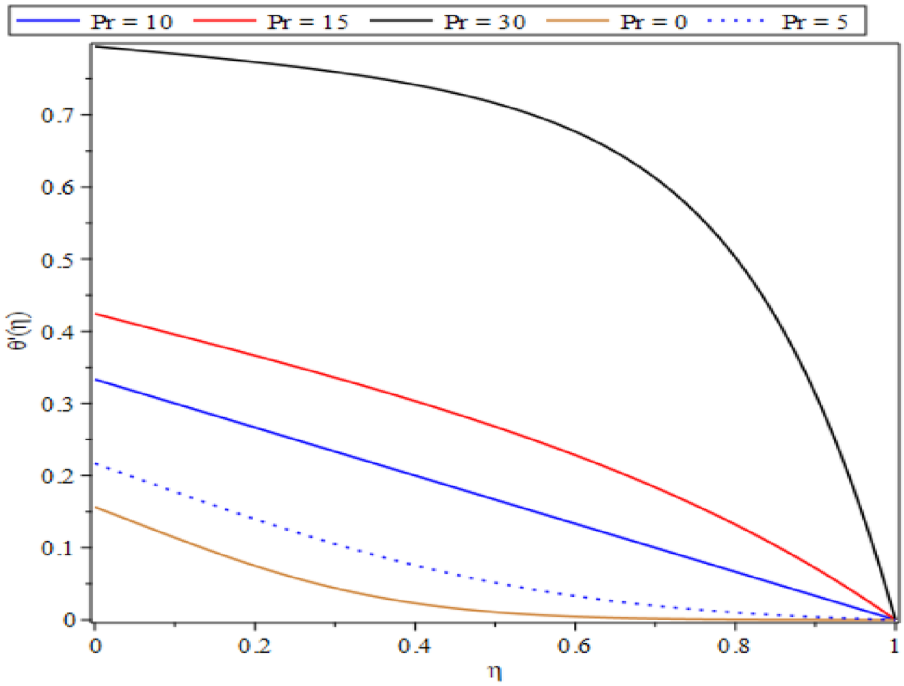


**Fig. 9Influence of Prandtl numberparameter on temperature profile**

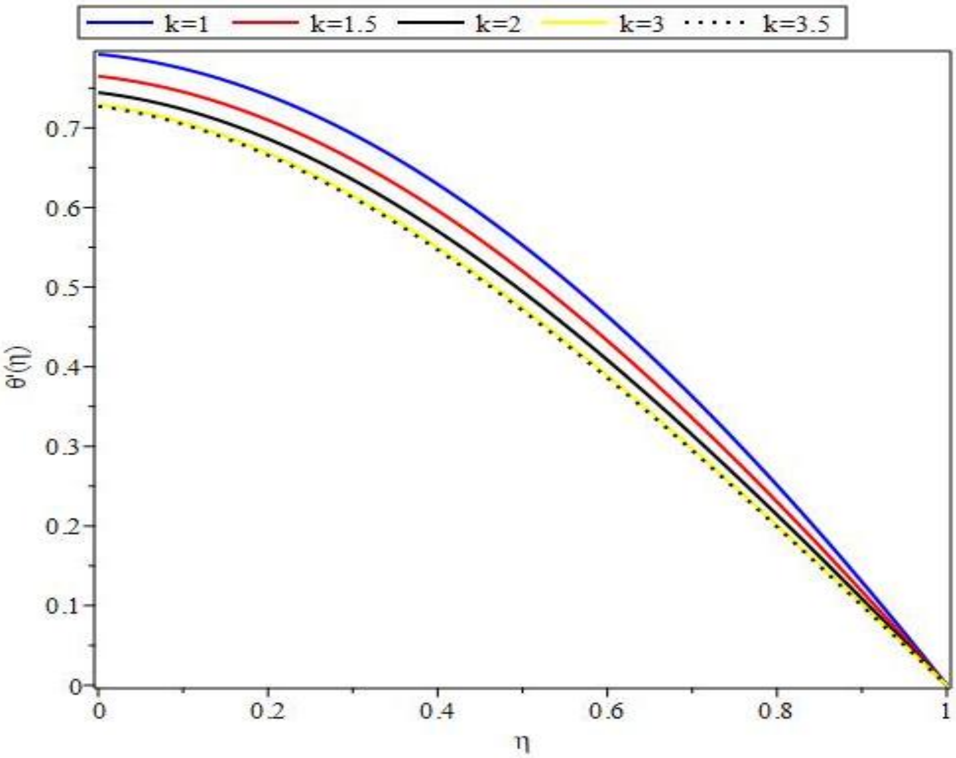


**Fig. 10Influence of permeability parameter on temperature profile**

Conversely, the Prandtl number exhibits an inverse relationship with the temperature profile. As the Prandtl number increases, thermal diffusivity decreases, confining heat closer to the wall and causing the temperature to decay more rapidly within the boundary layer. This results in a thinner thermal boundary layer and lower temperature levels.

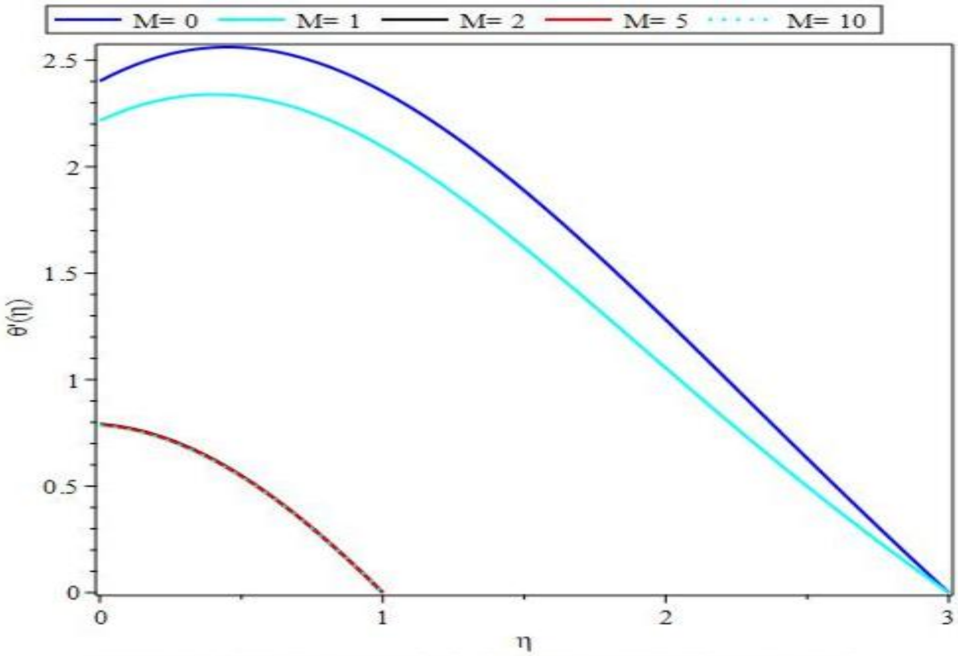


**Fig. 11Influence of magnetic parameter on temperature profile**

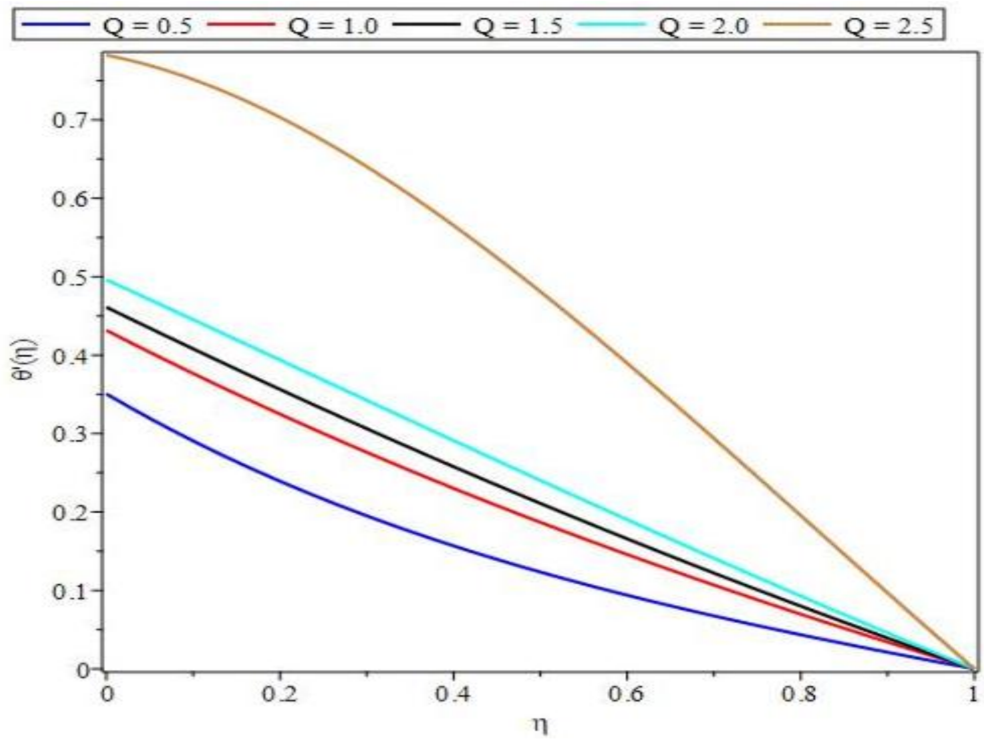


**Fig. 12Influence of heat generation/ absorption parameter on temperature profile**

The permeability parameter also reduces the temperature profile. Increased porous resistance weakens convective heat transport and promotes thermal dissipation within a thinner boundary layer, thereby lowering the fluid temperature throughout the flow region.

An increase in the magnetic field parameter leads to a decrease in the temperature profile. The stabilizing influence of the magnetic field suppresses thermal diffusion and enhances convective heat removal due to increased fluid motion, resulting in lower temperature values within the boundary layer.

In contrast, the heat generation/absorption parameter significantly increases the temperature profile. Internal heat generation acts as a volumetric heat source, raising the fluid temperature and thickening the thermal boundary layer. This effect is further amplified in nanofluids due to their enhanced thermal conductivity and energy storage capacity.

**Nusselt Number Profile**

The Nusselt number, representing the dimensionless surface heat transfer rate, responds distinctly to variations in governing parameters. An increase in the thermal radiation parameter causes a reduction in the Nusselt number. Although radiation elevates the fluid temperature, it smooths the temperature distribution near the wall, reducing the temperature gradient and thereby weakening conductive heat transfer at the surface.

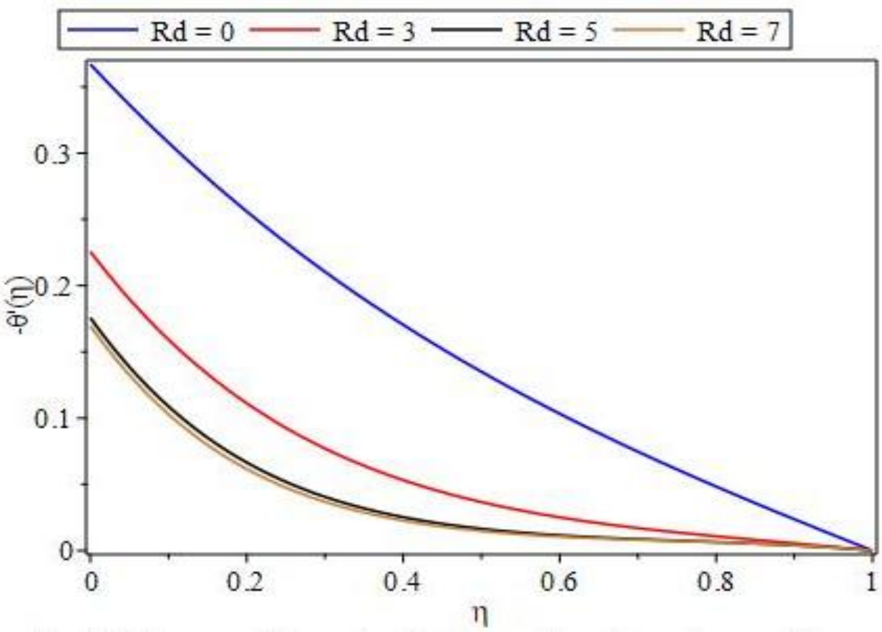


**Fig. 13Influence of thermal radiation parameter on Nusselt number profile**

Similarly, increasing the Prandtl number leads to a decrease in the Nusselt number. In the present MHD nanofluid system, dominant magnetic and viscous dissipation effects outweigh the expected enhancement in wall temperature gradient, resulting in reduced effective heat transport and lower surface heat transfer rates.

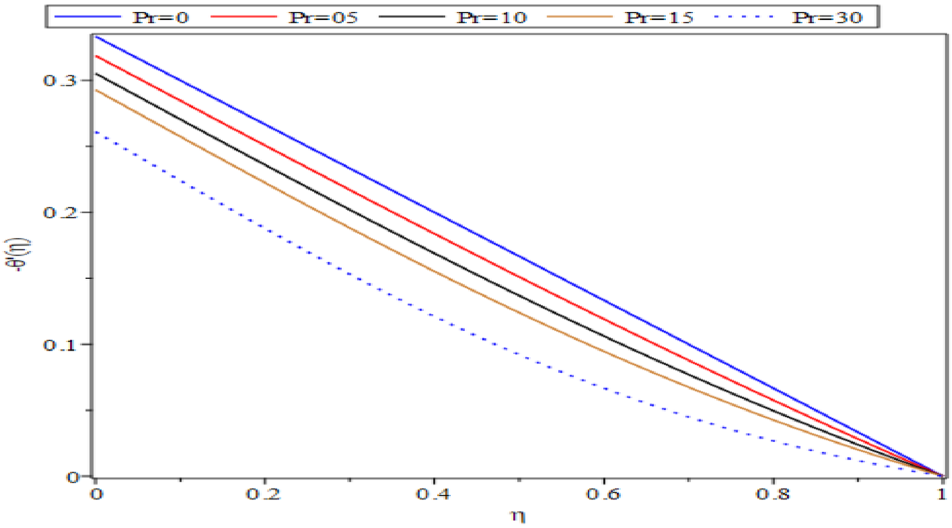


**Fig. 14Influence of Prandtl numberparameter on Nusselt number profile**

In contrast, the permeability parameter enhances the Nusselt number. Higher permeability reduces convective transport and thins the thermal boundary layer, which steepens the temperature gradient at the wall and increases the surface heat transfer rate, despite lower bulk fluid temperatures.

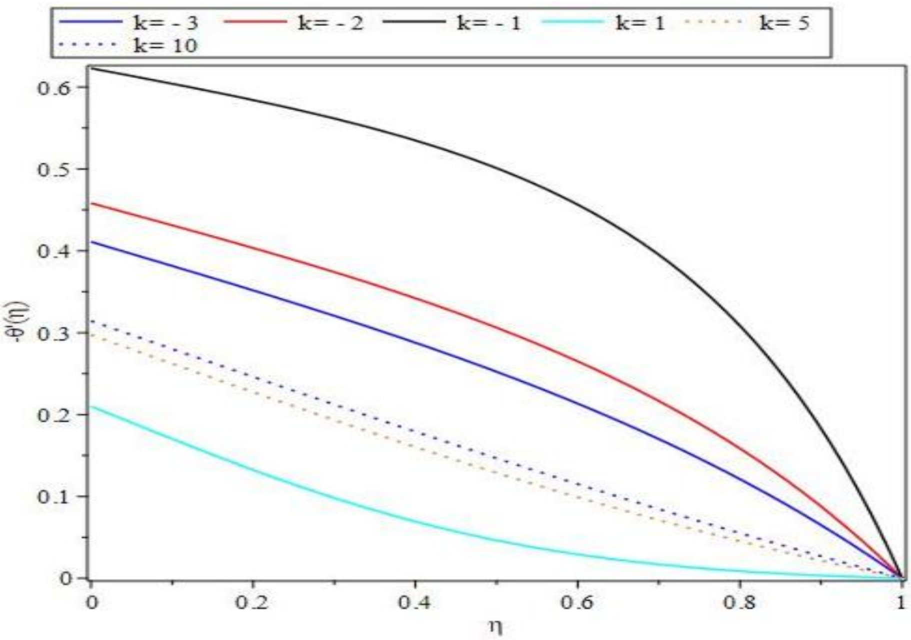


**Fig. 15Influence of permeabilityparameter on Nusselt number profile**

The magnetic field parameter also increases the Nusselt number. Enhanced fluid motion due to electromagnetic forces intensifies convective heat transfer and steepens the wall temperature gradient, leading to higher surface heat transfer rates.

Finally, the heat generation/absorption parameter is observed to increase the Nusselt number. Internal heat generation raises the thermal energy near the wall, producing a steeper temperature gradient at the surface and consequently enhancing the surface heat transfer rate, even though the momentum profile is suppressed.

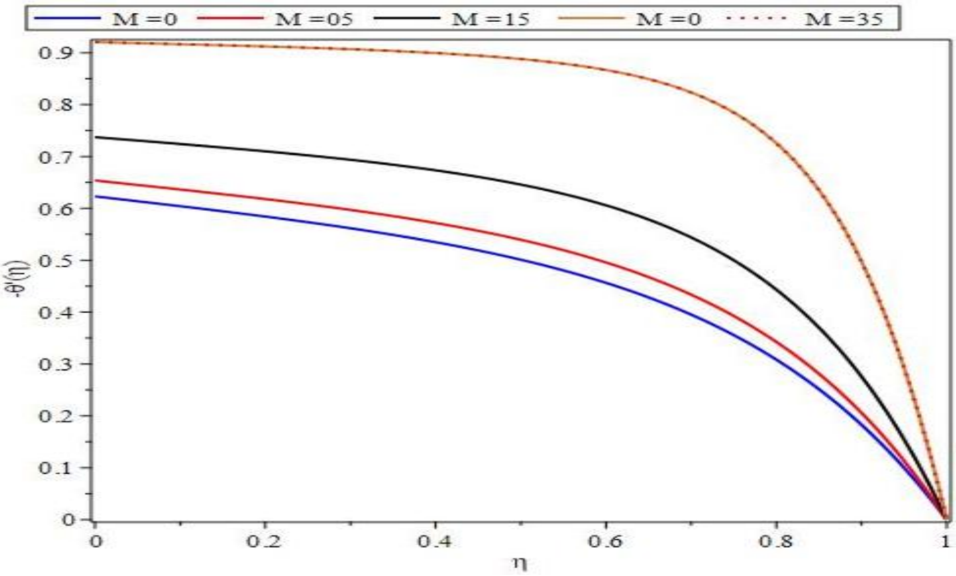


**Fig. 16Influence of magneticparameter on Nusselt number profile**

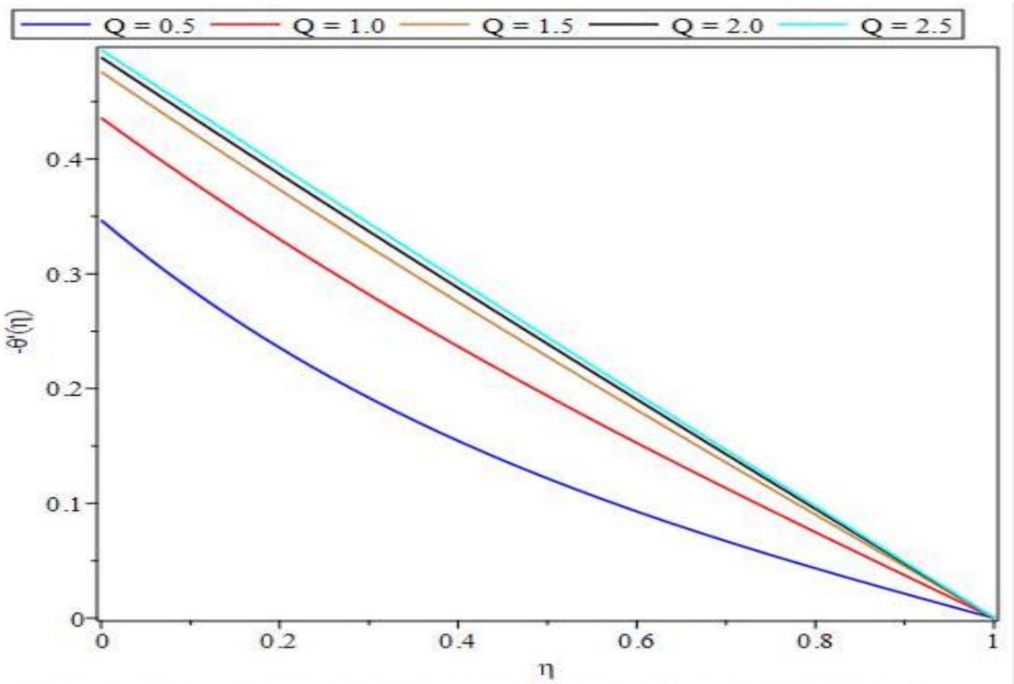


**Fig. 17Influence of heat generation/ absorptionparameter on Nusselt number profile**

## Conclusion

This study presented a comprehensive numerical investigation of magnetohydrodynamic nanofluid flow under the combined effects of thermal radiation, Prandtl number, permeability, magnetic field strength, and internal heat generation or absorption. By transforming the governing nonlinear partial differential equations into a coupled system of dimensionless ordinary differential equations and solving them numerically, the influence of key controlling parameters on momentum, thermal, and heat transfer characteristics was systematically analyzed.

The results demonstrate that thermal radiation and internal heat generation act as dominant thermal enhancement mechanisms, significantly increasing the fluid temperature while simultaneously suppressing momentum transport due to intensified thermal–magnetic coupling and resistive forces. In contrast, higher Prandtl numbers restrict thermal diffusion, leading to thinner thermal boundary layers and reduced velocity and temperature profiles. The permeability parameter introduces strong porous resistance, which decelerates the flow and lowers temperature levels, yet enhances surface heat transfer through boundary layer thinning. The magnetic field parameter emerges as an effective control mechanism, capable of enhancing momentum and surface heat transfer rates while reducing the thermal field via strengthened electromagnetic convection.

From a mathematical standpoint, the obtained results are consistent with the qualitative structure of the governing dimensionless equations and the imposed boundary conditions. The competing roles of diffusion, convection, radiation, porous drag, and Lorentz forces highlight the nonlinear coupling inherent in MHD nanofluid systems. The observed trends in the Nusselt number further emphasize that surface heat transfer is governed primarily by wall temperature gradients rather than bulk thermal energy.

Overall, the present analysis provides useful insight into the parametric sensitivity and transport behavior of MHD nanofluids in porous and radiative environments. The findings contribute to the theoretical understanding of coupled momentum–thermal transport in complex fluids and may serve as a reference framework for future extensions involving unsteady flow formulations, nonlinear radiation models, variable thermophysical properties, or hybrid nanofluid configurations within the same mathematical framework.

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**Authors' Contributions-** Each author made a corresponding contribution to the study. They came up with the research idea then studied the literature in unanimity. They worked cooperatively to write the initial draft of the manuscript.

**Conflict of Interest-** Authors declare that they do not have any conflict of interest.

**Data Availability-** none

**Conflicts of Interest**

The author declares no conflicts of interest.

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