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THERMAL RADIATION AND SUCTION/INJECTION EFFECTS ON MIXED CONVECTION HEAT TRANSFER IN A POROUS COAXIAL CYLINDRICAL CHANNEL

***[1]Abdulsalam Shuaibu, [2]Yakubu Bello, [3]Auwal Musa Kallamu, [1]Godwin Ojemeri and [4]Rashida Abdulrauf**

[1]Federal University of Agriculture, Zuru, P.M.B 28, Kebbi State, Nigeria.
[2]Department of Mathematics, Faculty of Science, Air Force Institute of Technology, P. M. B. 2104, Kaduna State, Nigeria.
[3]Federal University, Kalgo, PMB 1157, Birnin Kebbi, Kebbi State, Nigeria.
[4]Usmanu Danfodiyo University P.M.B. 2346 Sokoto, Nigeria.

*Corresponding authors' email: shuaibuabdulsalam@gmail.com

ABSTRACT

This study investigates the mixed convection heat transfer flow within a coaxial cylinder filled with a homogeneous porous medium. The mathematical model integrates the influences of heat radiation, Navier slip, and wall suction/injection. The Darcy–Brinkman model and the Rosseland approximation for radiative heat flux are employed to adjust the governing equations for momentum and energy formulated in cylindrical coordinates. Boundary conditions that account for slip velocity and mass suction/injection transfer are applied at the cylinder walls. Analytical solutions are obtained by solving the resulting nonlinear coupled equations. Parametric calculations indicate that injection promotes fluid acceleration within the annulus, while suction mitigates flow reversal and enhances thermal stability. Navier slips reduce skin friction at both the lower and upper cylindrical walls. Nevertheless, MHD reduces wall shear stress, especially near the inner cylinder. Thermal radiation increases the thermal boundary layer and elevates the temperature and velocity domains. Furthermore, it was demonstrated that the Darcy porous media significantly enhanced the velocity domain, leading to increased permeability with a rising value of Da. The findings provide significant insights for engineering designs involving porous annuli, thermal insulation devices, catalytic reactors, membrane filtration, and energy systems.

Keywords: Suction/Injection, Navier Slip, Thermal Radiation, Darcy Porous Medium, Coaxial Cylinder

INTRODUCTION

Recently, scientists have shown considerable interest in magnetohydrodynamic boundary layer fluxes within porous media. The characteristics of the final product can be regulated by manipulating heat transfer in electrically conductive fluids by the application of a magnetic field. Academics in literary studies have investigated the effects of Lorentz forces (Jha and Gwandu 2020, Harshad 2021, Veerakrishma *et al*. 2020). Lorentz forces significantly affect the temperature distribution, as evidenced by their findings. The rate of heat transmission decreases as the Lorentz force values grow. Shawky (2012) investigated the stretching sheet problem under the influence of a magnetic field. This study by Harshad (2021) comprehensively analyzes the influence of heat radiation on magnetohydrodynamic (MHD) flow. This inquiry focuses on the heat and mass transmission characteristics of a micropolar fluid confined between two vertical walls. Injectors, electric transformers, cooling systems utilizing metallic plates, and MHD turbines represent a few of the numerous practical applications that have advanced magneto-hydrodynamics (MHD) research to prominence in recent decades. Numerous nuclear power reactors utilize chemical energy technologies. This technology involves the utilization of multi-head diaphragm pumps to circulate electrically conductive fluids. Hamza *et al*. (2022) investigated the heat transport in an Arrhenius-equivalent microchannel in relation to an artificially induced magnetic field. The implementation of superhydrophobicity in microchannels was seen to influence microscale behavior through slip flow, decreased friction, and reduced liquid-solid interactions, as noted by Jha and Gwandu (2019). Valuable information concerning the applications of MHD is available in the literature (Jamaludin *et al.* 2020, & Kurma *et al* 2017). There could be supplementary advantages in spacecraft aerodynamics, nuclear energy facilities, and solar technologies. The numerous advantages of thermal radiation have led a significant number of scientists to investigate its impacts across diverse physical configurations. Hamza *et al*. (2023) investigated a magnetized natural convection fluid traversing a heated porous superhydrophobic microchannel, focusing on the influences of thermal radiation and superhydrophobicity. Shah *et al*. (2023) investigated heat transmission in mixed-mode high-pressure Casson flows influenced by chemical and thermal processes related to fluid properties. Hasan *et al*. (2020), Gireesha *et al*. (2020), and Goud *et al*. (2023) examined the impact of heat radiation on free convection flow and elaborated on its scientific and technological implications. References (Bejawada & Nandeppanavar, 2023, and Parthiban & Prasad, 2023) offer additional insights into preliminary investigations related to the application of heat radiation. In fluid mechanics, "injection" refers to the introduction of a fluid into a system, as illustrated by a blood transfusion, whereas "suction" involves the removal of fluid from a system. The concurrent occurrence has aroused our curiosity in the functions of suction and injection in diverse fluids, as highlighted by the previously described applications. Uwanta and Hamza (2014) investigated the effects of suction and injection on the dynamics of unsteady hydromagnetic convective flow of a reactive viscous fluid between vertical porous plates with thermal diffusion. The research demonstrates that the velocity profile is superior for injection relative to suction. In a specific period, Jha *et al*. (2018) investigated the effects of suction and injection on hydromagnetic natural convection flow in vertical plates. The utilization of suction or injection has been recognized as an effective method for regulating fluid flow within the channel, as noted by Jha et al. (2015). The findings of their experiments demonstrated that the augmentation of suction/injection leads to a rise in the temperature differential between the wall and the surrounding environment.

Consequently, a decrease in convection within the microchannel occurs. The research conducted by Jha et al. (2022) examined the impact of suction and injection on the dynamics of spontaneous convection in transient magnetohydrodynamics (MHD). Falade et al. (2017) examined the effects of suction and injection on the dynamics of transient oscillatory magnetohydrodynamic flow. When a channel wall or flat surface contains apertures or openings that allow fluid leakage, suction, and/or injection takes place. This phenomenon is substantiated by studies undertaken by Mishra et al. (2002), Chaudhary and Jain (2007), and Khalid et al. (2015). Numerous studies have recorded the impacts of injection and suction. To achieve this purpose, Hamza and Abdulsalam (2022). Recently, an implicit finite difference scheme was employed alongside the homotopy perturbation approach to investigate a chemically reactive fluid in an exothermic process within a vertical channel in a distinct experiment. Shah *et al* (2019) offer assessments of suction/injection applications. Alvarez *et al*. (2022) examined the finite element approach for double-diffusive natural convection within porous media. It is essential to note that injection on the hot plate elevates the skin friction within the channel. Abbas *et al*. (2020) examined the widespread application of porous media in the heating and cooling of electrical systems inside various industrial processes. Bordoloi *et al*. (2023) analytically solved a constant-viscosity, incompressible, two-dimensional hydromagnetic free convective flow.

This study provides a distinctive contribution to the understanding of magnetohydrodynamic (MHD) flow and heat transfer within a coaxial radial cylindrical system affected by thermal radiation, suction, and injection phenomena. Previous studies have typically focused on either magnetohydrodynamic flow or slip flow independently, mainly inside uncomplicated cylindrical geometries. Nonetheless, few have investigated their cumulative effect within a coaxial annular arrangement, which is more relevant to many technical contexts involving concentric pipelines, nuclear reactors, and heat exchangers. The primary contribution of this study is the comprehensive integration of magnetohydrodynamics, radiative heat transfer, and wall mass transfer (suction/injection) processes within a radially extended annulus. The formulation encompasses the interplay between the Lorentz force and the variations in thermal radiation, influencing both the velocity and temperature fields of the conducting fluid. Analytical and numerical solutions derived from the governing equations illustrate how these parameters can be modified to enhance or impede flow and heat transfer efficiency, depending on the specific operational conditions. The significance of this study lies in its practical applicability to numerous advanced thermal and fluid engineering systems. The results can improve the design and performance of MHD power generation units, as magnetic manipulation of fluid dynamics enhances energy conversion efficiency, and geothermal cooling systems, where suction and injection promote heat dissipation. This study fulfills a critical knowledge gap by presenting a comprehensive model that simultaneously integrates MHD effects, radiative heat transfer, and wall mass flow in coaxial geometries. It thereby provides both theoretical insight and engineering relevance.

MATERIALS AND METHODS

A radial magnetic field is utilized to investigate the steady, fully developed, laminar free convective flow of a conducting viscous fluid within a vertical coaxial cylinder formed by two infinitely permeable vertical lines. The z'-axis, designated as the cylinder's axis, extends vertically upward against the force of gravity, while the r'-axis extends in the opposite direction. Refer to Figure 1 for the definitions of a and b, denoting the inner and outer cylinder radii, respectively. A magnetic field is applied radially outward. Heat is consistently transferred into the inner cylinder. In the context of fully developed flow in infinitely long cylinders, the sole relevant radial coordinate for flow generation is r'. The governing equations can be articulated as follows, employing the standard Boussinesq approximation:

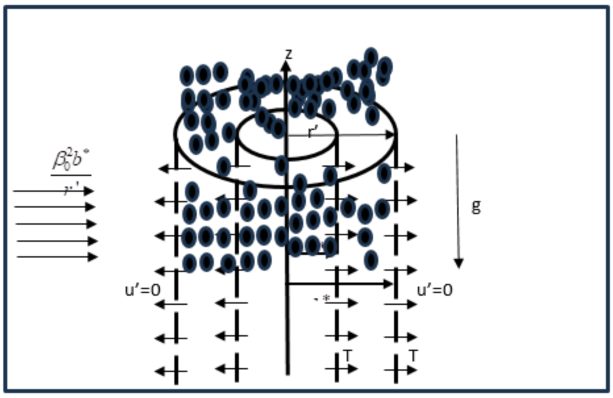

Figure 1: Model Illustration

The dimensional governing equations of the model are given as

$$\frac{v_0}{r'}\frac{du'}{dr'} = v\left[\frac{d^2u'}{dr'^2} + \frac{1}{r'}\frac{du'}{dr'}\right] - \frac{\sigma B_0 y_0^2}{\rho v}u' - (\frac{1}{k})u' + +g\beta(T' - T_\infty') - \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad (1)$$

$$\frac{v_0}{r'}\frac{dT'}{dr'} = \alpha\left[\frac{d^2T'}{dr'^2}\frac{1}{\rho c\rho}\frac{dqr}{dr'}\right] + \alpha\left[\frac{1}{r'}\frac{dT'}{dr'}\right] \qquad (2)$$

The corresponding initial and boundary conditions are given as:

$$u' = \frac{k}{\alpha}\frac{du'}{dr'}, \qquad \frac{dT'}{dr'} = \frac{-q'}{k} \qquad at \qquad r' = a \qquad (3)$$

$$u' = 0, \qquad T' = T_\infty' \qquad at \qquad r' = b \qquad (4)$$

The non-dimensional quantities and parameters are defined as

$$\left.\begin{aligned} & u = \frac{vu'}{g\beta\alpha^2\Delta T'}, r = \frac{r'}{a}, \lambda = \frac{b}{a}, S = \frac{V_0 a}{v}, Gr = \frac{g\beta(\theta_1 - \theta_0)}{v^2} \\ & \theta = \frac{T' - T_\infty^0}{\Delta T}, M^2 = \frac{\sigma B_0 y_0^2}{\rho v}, \gamma = \frac{k}{\alpha a}, 1 + R_d = \frac{1}{\rho c\rho}\frac{dqr}{dr'} \\ & \mathrm{Re} = \frac{u_0}{v}, \quad A = \frac{\partial p}{\partial x}, Da = \frac{kv}{v} \end{aligned}\right\} \qquad (5)$$

Using equation (4) in equations (1) and (2) yields the following:

$$\frac{1}{r}\frac{du}{dr}-\frac{S}{r}\frac{du}{dr}-\frac{1}{r^2}\left(\frac{1}{Da}+M^2\right)u+Gre\theta=0 \tag{6}$$

$$(1+R_d)\frac{d^2\theta}{dr^2}+\frac{1}{r}\frac{d\theta}{dr}-\frac{S}{r}\frac{d\theta}{dr}=0 \tag{7}$$

$$u=\gamma\frac{du}{dr}, \qquad \frac{d\theta}{dr}=-1 \qquad at \qquad r=1 \tag{8}$$

$$u=0 \qquad \theta=0 \qquad at \qquad r=\lambda \tag{9}$$

By substituting the conditions (8) and (9) into the temperature and momentum equations (6) and (7), the analytical expressions for the temperature and velocity fields are obtained as follows:

$$\theta(r)=C_3r^{k_6}+C_2 \tag{10}$$

$$u(r)=Ar^{k_1}-\frac{Gre}{1-S}\left[\frac{C_3r^{m+2}}{k_3}+\frac{C_2r^2}{k_4}\right] \tag{11}$$

The rate of heat transfer and the wall shear stress are obtained by differentiating the analytical solutions of temperature and velocity with respect to r, and evaluating the resulting expressions at $r=1$ and $r=\lambda$

$$Nu_1=\left.\frac{d\theta}{dr}\right|_{r=1}=k_6C_3 \tag{12}$$

$$Nu_\lambda=\left.\frac{d\theta}{dr}\right|_{r=\lambda}=k_6C_3\lambda^{k_6-1} \tag{13}$$

$$\tau_1=\left.\frac{du}{dr}\right|_{r=1}=k_5A^{k_5}-\frac{Gre}{1-S}\left[\frac{C_3(m+2)}{k_7}+\frac{2C_2}{k_8}\right] \tag{14}$$

$$\tau_\lambda=\left.\frac{du}{dr}\right|_{r=\lambda}=k_5A^{2k_5}-\frac{Gre}{1-S}\left[\frac{C_3(m+2)\lambda^{m+1}}{k_7}+\frac{2C_2\lambda}{k_8}\right] \tag{15}$$

RESULTS AND DISCUSSION

The analytical results on the effect of thermal radiation and suction/injection on mixed convection heat transfer in a porous coaxial cylindrical channel are presented and discussed in this section. A thorough analysis is carried out on the impact of the controlling physical parameters on the distributions of both velocity and temperature. Focusing on the effects on flow and temperature fields of the radiation, suction/injection, magnetic, and mixed convection parameters is essential. The change in velocity and temperature profiles for various values of the regulating parameters is shown graphically. We also examine the related effects on the Nusselt number, which measures the rate of heat transfer, and the skin friction coefficient, which measures the wall shear stress, to give a physical understanding of the transport processes that control the system. Both Figure 2a and 2b show how thermal radiation changes the distribution of fluid temperature and velocity in the annular region. An increase in the radiation parameter causes a corresponding rise in fluid temperature over the annular region, as seen clearly in the picture. Theoretically, this happens because thermal radiation acts as an additional energy transfer mechanism, increasing the thermal energy inside the fluid layers; hence, when the temperature profile rises, the fluid velocity rises as well. The impact of suction on the distribution of fluid temperature and velocity in the annular space is seen in Figures 3a and 3b. The temperature of the fluid inside the annular region drops when the suction parameter is raised. The thickness of the thermal and velocity boundary layers is reduced due to the physical removal of fluid particles from these layers by suction. The overall fluid temperature drops as the thermal barrier layer gets thinner because less heat is retained within the flow. Suction regulates the excessive heat accumulation in the system, as the cooling impact is seen across the annular gap. Aerodynamics and boundary layer control are two areas where suction finds application. Thermal Management Systems, Combustion Chambers, Furnaces, and more components.

Figure 4a and 4b showed the effects of injection on temperature and velocity profiles, and computational analysis showed that increasing the injection parameter in a fluid flow system usually makes the whole flow domain hotter and faster. By injecting additional momentum and energy into the boundary layer, fluid injection enhances convective heat transfer and sharpens the fluid's motion near the wall. Enhanced momentum and thermal boundary layer thickness cause increased velocity and temperature dispersion inside the flow zone as the injection rate increases. The function of the Navier slip and the magnetic parameter at the boundary is seen in Figures 5a and 5b. Since the boundary surface becomes more "slippery" as the slip parameter increases, the fluid particles have an easier time sliding along the wall. Because there is less friction between the fluid and the boundary surface, the fluid's velocity increases dramatically near the wall and throughout the flow domain. Simplified, a higher slip value and faster, smoother fluid motion are both achieved by mitigating the effects of viscous drag at the interface. However, in 5b, the action magnetohydrodynamic (MHD) was seen; increasing the MHD parameter (magnetic field intensity) greatly lowered fluid velocity within the flow domain. The Lorentz force, a resistive force generated by the interaction of a magnetic field with an electrically conducting fluid, provides an explanation for this occurrence. The Lorentz force works against the mobility of particles in a fluid, increasing the resistance to flow and decreasing their total velocity. To slow down and stabilize the flow of magnetically sensitive fluids, such as electrolytes, plasmas, or molten metals, a stronger magnetic field is required. The velocity field is enhanced when the Darcy porous parameter is increased (Figure 6a and 6b). This is due to the fact that a higher permeability reduces the drag generated by the porous matrix, making it easier for the fluid to flow through the annulus. Just as larger temperature gradients provide stronger buoyant forces, which quicken the flow, the mixed convection parameter does the same thing. Catalytic reactors, annular heat exchangers, thermal insulation systems, geothermal extraction, and other engineering designs involving porous media rely on this linked behaviour. A significant influence on momentum transport is buoyancy-driven motion and permeability. In Figure 7a, we can see that when the value of MHD increases at the bottom of the inner cylinder, skin friction decreases; however, in Figure 7b, we can witness the opposite behaviour at the top of the inner cylinder, demonstrating the effect of MHD on friction force. Shear stress was shown to be affected by the suction parameter in Figures 8a and 8b. When the suction parameter is increased, the skin friction increases at r=1, but it tends to decrease at r= the annular wall. Figures 9a and 9b showed the effects of the Darcy porous media on skin friction; in the bottom annular channel, friction was found to be higher, while in the top channel, it was found to be lower. Thermal radiation was shown to be repelled by mixed convection in Figures 10a and 10b. Observed in Figure 10a, a rise in the mixed convection parameter results in an increase in skin friction, whereas the contrary trend is shown in Figure 10b. According to the results shown in Figure 11a and 11b, which analyzed the effects of injecting fluid against heat radiation, increasing injection values cause skin friction to rise in Figure 11a, but the opposite happens in Figure 11b. Raising the slip flow parameter reduces skin friction on the heated and cooled circular walls, as shown in Figures 12a and 12b, which explain the effects of Navier slip on skin friction. The decrease in skin friction is caused by a decrease in viscous effects near the boundary, which occurs as a result of sliding. A decrease in shear stress is achieved by a decrease in momentum transfer from the wall to the fluid, which is caused by an increase in the slip parameter, which leads to a modest increase in fluid velocity at the wall. The method has found use in temperature management systems, coating processes, and lubrication protocols. Table 1 shows how the current results are supported by the previous research done by Gambo (2022). It is clear from the comparison that the two results are very similar, especially when the thermal radiation parameter is set to zero. This means that the governing equations and boundary conditions used in this work are the same as those used by Gambo (2022) when thermal radiation effects are not included. The accuracy and reliability of the present model and computational methods are confirmed by the near alignment of numerical quantities.

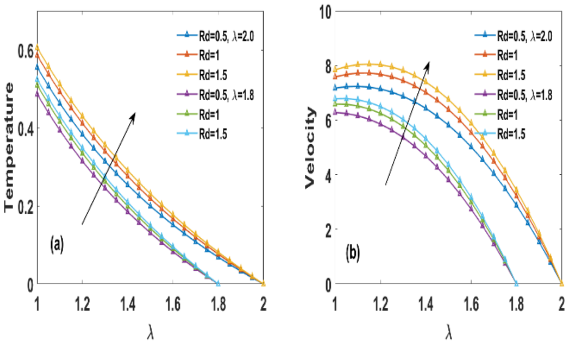

Figure 2: Influence of Thermal Radiation on Velocity and Temperature Domain

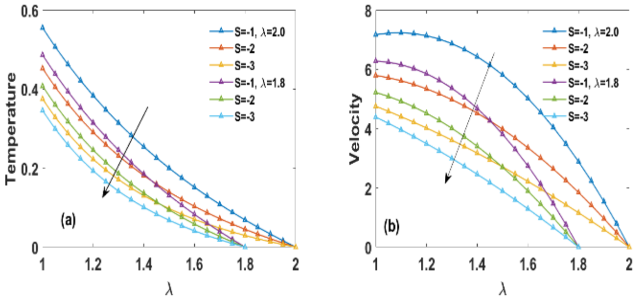

Figure 3: Influence of Suction on the Temperature and Velocity Domain

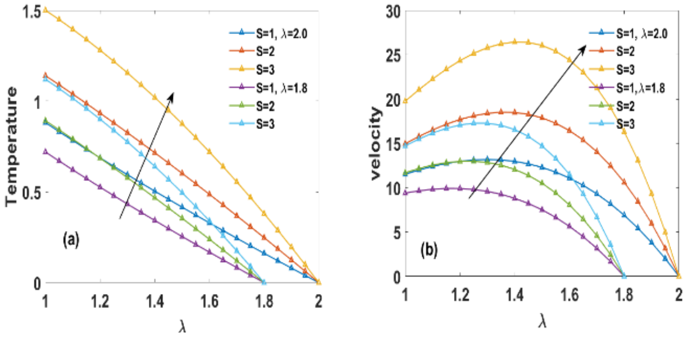

Figure 4: Influence of Injection on the Temperature and Velocity Domain

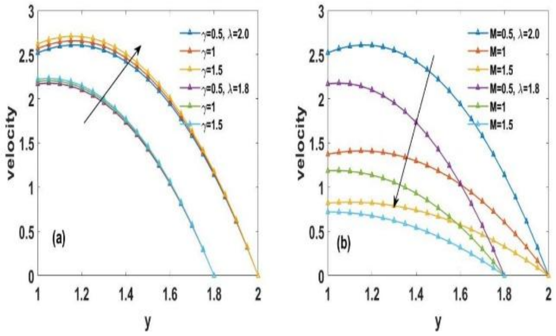

Figure 5: Influence of Navier Slip and Magnetic Parameter on the Velocity Domain

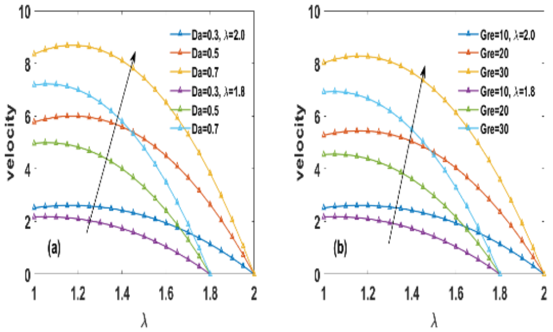

Figure 6: Influence of Darcy Porous Medium and Mixed Convection Parameter on the Velocity Domain

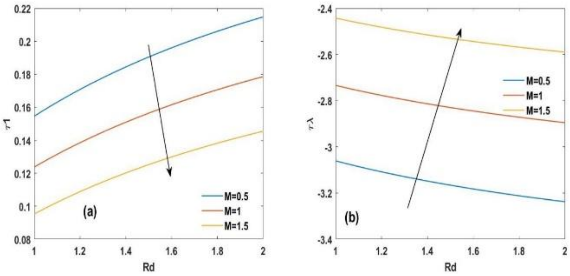

Figure 7: Skin Friction for MHD against Thermal Radiation

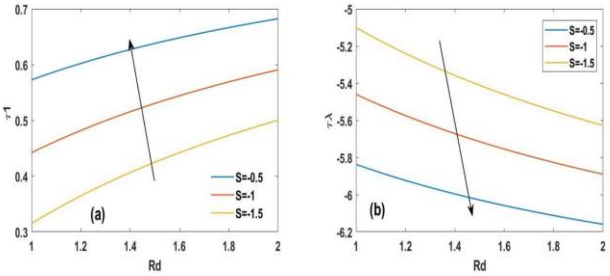

Figure 8: Skin Friction for Suction against Thermal Radiation

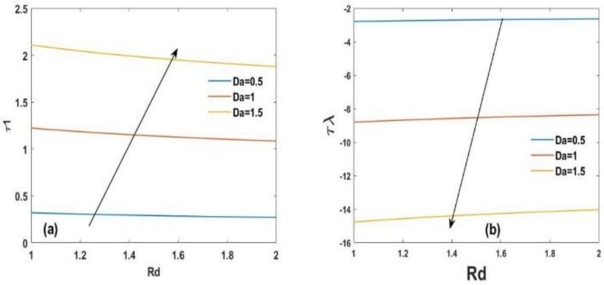

Figure 9: Skin Friction for Darcy Porous Medium against Thermal Radiation

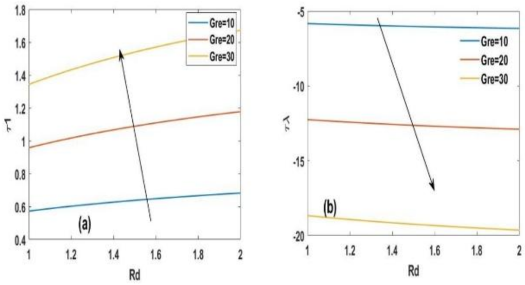

Figure 10: Skin Friction for Mixed Convection against Thermal Radiation

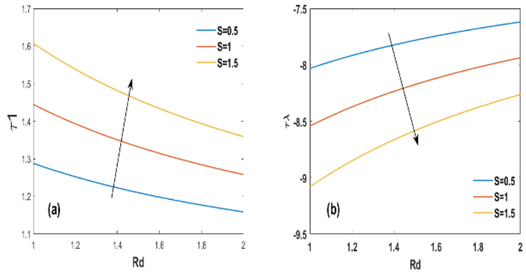

Figure 11: Skin Friction for Injection against Thermal Radiation

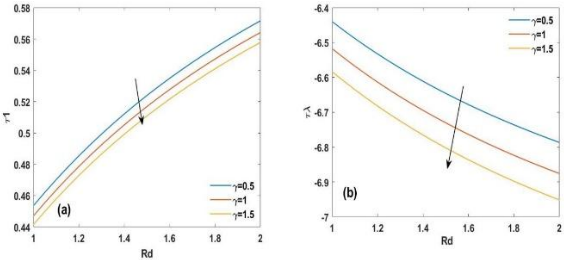

Figure 12: Skin Friction for Navier Slip Parameter against Thermal Radiation

Validation of the Result

Table 1: Shows Numerical Validation for the Current Study and Gambo (2022)

λ	**Gambo (2022) Temperature** $\theta(R)$	**Current work Temperature** $\theta(R)$	**Gambo (2022) Velocity** $u(R)$	**Current work Velocity** $u(R)$
0.5	2.0078	2.0078	1.6545	1.6547
1.0	0.1772	0.1772	-0.2132	-0.2132
1.5	0.8008	0.8008	-21.4898	-21.4898
2.0	-1.0056	-1.0056	-71.9723	-71.9729
2.5	-1.4818	-1.4818	-139.794	-139.794

CONCLUSION

This research details an examination of heat transfer and slip flow in magnetohydrodynamic (MHD) natural convection inside a coaxial cylindrical annulus, including the mutual effects of thermal radiation, mass suction/injection, and Navier slip. The impact of critical physical factors on the temperature and velocity fields was investigated by solving the governing nonlinear momentum and energy equations under suitable boundary conditions.

This is a synopsis of the study's main points:

i. It was discovered that thermal radiation improved the fluid's temperature and velocity characteristics. With more energy flowing into the system from the radiative heat flux, heat transfer improves, and convective motion in the annular area becomes greater.
ii. Due to the strengthening of the boundary layer and acceleration of fluid movement in the hot channel caused by the influx of mass and energy into the domain, injection significantly improves both fluid temperature and velocity.
iii. The fluid near the heated wall was found to be decelerated by suction, resulting in a decrease in velocity and temperature at the border zone. Efficacious cooling and flow stability are both enhanced by this effect.
iv. A retarding Lorentz force, which operates in the opposite direction of the flow, is produced by magnetohydrodynamic (MHD) processes. The fluid's velocity is reduced by this resistive force, which stabilizes the flow field and suppresses motion.
v. The flow movement was found to be escalated by the Navier slip condition, which allowed the fluid to slide more easily along the wall. Because of the slippery action at the hot border, the flow performance is improved, and the frictional resistance is reduced.

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Appendix

$$B=\frac{1}{Da}+M^{2},m=1-\frac{1-S}{D},C_{3}=\frac{-1}{1-\frac{1-S}{D}},m=1-\frac{1-S}{D}$$

$$C_{2}=C_{3}\lambda^{1-\frac{1-S}{D}},k_{3}=\frac{C_{3}\lambda^{m+2}}{m+2-\frac{B}{1-S}},k_{4}=\frac{C_{3}\lambda^{2}}{2-\frac{B}{1-S}},k_{6}=$$

$$A=\frac{Gr}{1-S}\lambda^{-\frac{B}{1-S}}\left[k_{3}+k_{4}\right],k_{7}=m+2-\lambda,k_{8}=2-\lambda$$