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Effect Of Magnetic Field on Couple Stress Ferromagnetic Micropolar Fluid Heated from Below in Porous Medium

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This study investigates the effect of a magnetic field on the dynamics of a couple stress ferromagnetic micropolar fluid heated from below in a porous medium. Micropolar fluids are characterized by micro-rotations of fluid particles, and couple stress fluids account for higher-order stresses in fluid flow. They are significant in modelling non-Newtonian fluid behavior in various engineering and biological applications. Another layer of complexity added is due to the interaction between the fluid's magnetic properties and the applied field, affecting the flow and heat transfer characteristics of the fluid. The governing equations for momentum, energy, and magnetic field interactions are thus formulated using the appropriate boundary conditions that include no-slip conditions at the fluid-porous medium interface and temperature boundary conditions in this work. This paper will therefore look at the interaction of thermal buoyancy forces, magnetic field-induced body forces, and the micropolar nature of the fluid in a porous medium. Assuming conditions of steady-state, weak magnetic field, and Bossiness approximation, the mathematical model is solved. The analytical solutions for fluid velocity and temperature distribution are obtained, while numerical simulations are carried out to analyze the impact of different strengths of the magnetic field on flow and thermal profiles. The simulation results indicate that the magnetic field has a strong influence on the temperature profile and velocity profile of the fluid, especially in the boundary layers. The magnetic field tends to stabilize the flow, reducing the heat transfer efficiency in some conditions. This study provides new insights into the combined effects of magnetic fields and couple stress fluids in porous media, offering potential applications in heat transfer, lubrication, and fluid dynamics in engineering systems. Further exploration of these effects in more complex configurations is recommended for practical applications.

Keywords: Magnetic field, couple stress fluid, micropolar fluid, porous medium, heat transfer.

1. Introduction

In general, traditional Newtonian fluids used in the study of fluid dynamics are not good enough to describe real-world applications. In fact, couple stress fluids are a subclass of non-Newtonian fluids where higher-order stresses are included in the behavior of the fluid. These stresses are produced by the rotation of interactions of fluid particles and are crucial for micro- and nano-scale systems. Coupled stress fluids play a very critical role in engineering applications, particularly in lubrication, where unique stress characteristics lead to reduced wear and friction and in bio-fluid dynamics, in which they represent the behavior of blood and other bodily fluids in different mechanical and environmental conditions. They are also important in heat transfer applications because their enhanced properties can improve the thermal conductivity of the fluid, thus managing dissipation more efficiently [1].

Characterization of the fluid medium is possible by means of another very essential class of non-Newtonian fluids: micropolar fluids. While ordinary fluids lack all kinds of particle constituents with associated micro-rotations, such a feature occurs in the constitutive particles of micropolar fluids and because of the presence of such a new degree of freedom for their constituent particles [2]. Micro-rotations bring in specific effects to the fluid flows particularly at the application of some external forces like magnetic fields or temperature gradients. Due to the fluid being able to realistically describe its behavior within systems having fluid with a rotation motion in engineering applications, it is recommended. An example could be the flow of blood with the industrial application or geological flow as well as its study in detail. Modeling in micropolar fluids has turned out to be critical especially because classical models have failed in giving satisfactory descriptions regarding the complicated dynamics involved in their flows [3].

Yet another complex category of fluid behavior under the influence of magnetic fields is ferromagnetic fluids. These are composed of magnetic particles suspended in a carrier fluid. Ferromagnetic fluids display various properties when an external magnetic field interacts with ferromagnetic particles inside the fluid, causing changes in flow behavior, such as viscosity and flow stability, and sometimes changes related to heat transfer. Such effects become meaningful in magnetic fluid seals, drug delivery systems, and cooling systems when control over manipulation of fluid by a magnetic field is helpful. Knowledge regarding magnetic fields having an influence on ferromagnetic fluids will facilitate the designing of the system that depends on such exclusive properties [4].

Porous media become complicated while studying them in conjunction with ferromagnetic micropolar fluids. Porous media consist of a solid matrix containing voids or pores; these types of media are commonly encountered in nature and industrial processes, such as the filtration of groundwaters, oil and gas extractions, and heat exchangers. Flow in porous media is very different from the open-channel flow because resistance to the flow of fluid through porous media exists in the solid matrix [5]. With magnetic fields, it is observed that the influence increases on the flow patterns and the heat transfer characteristics in these media.

Understanding the effects of a magnetic field on ferromagnetic micropolar fluids in a porous medium is vital for systems that require efficiency enhancement, such as energy storage, enhanced oil recovery, and filtration processes [6].

In systems heated from below, it is the buoyancy-driven force created by temperature gradients that can drive fluid flows. Buoyancy effects in natural and engineered systems can become important in some applications, as for example geothermal heat transfer or cooling electronic components. If the buoyancy-driven flow couples with external forces like magnetic fields, then complexity of the patterns may arise such that the flow structure must be properly understood for best design of the systems [7]. These effects may complicate fluid dynamics further if coupled with the unique characteristics of micropolar and couple stress fluids, requiring detailed study in interaction between thermal gradients, magnetic fields, and complex fluid behavior in porous media [8].

The significance of research into ferromagnetic micropolar fluids in porous media, particularly under thermal gradients, can be realized with potential applications in a variety of fields of engineering, such as better heat exchangers, magnetic fluid-based cooling systems, and porous media reactors [9]. Manipulation of fluid flow and heat transfer using a magnetic field has potential benefits for control over the performance of a system and to improve its efficiency. Understanding how such fluids behave under different thermal and magnetic conditions is crucial in the design and optimization of systems where such fluids are used [10].

This work aims to investigate the combined effects of magnetic fields, couple stress properties, and micropolar behavior in ferromagnetic fluids within a porous medium heated from below. Primarily, it tries to find out the influence of these forces on fluid flow, heat transfer, and system efficiency as a whole. In this direction, this paper is dedicated to contribution toward the creation of more efficient and effective systems for working with ferromagnetic micropolar fluids in porous media based on deeper understanding of the interplay between these forces and fluid characteristics. Key Contributions of this article are,

1. The study develops a model for the behavior of ferromagnetic micropolar fluids in porous media, accounting for magnetic field effects, couple stress properties, and micropolar dynamics.

2. It investigates how magnetic fields influence the flow and heat transfer characteristics of these fluids, enhancing the understanding of their behavior under different conditions.

3. The research explores the effect of heating from below on the fluid dynamics, focusing on buoyancy-driven flow and its interaction with magnetic forces in porous media.

4. The study provides insights into the changes in heat transfer efficiency due to the combined effects of magnetic fields and complex fluid properties.

5. The findings contribute to the design of advanced engineering systems such as enhanced heat exchangers, magnetic fluid-based cooling systems, and porous media reactors, where ferromagnetic micropolar fluids are used.

This section introduces the problem, followed by a mathematical formulation describing the governing equations along with the boundary conditions and the role of magnetic fields in the system. Solution methodology discusses both analytical and numerical solutions of the governing equations. Graphical analyses for velocity and temperature profiles are carried out with conditions set to vary, and the results have highlighted the influence of the magnetic field involved. Finally, the discussion, conclusion, and future works sections provide insights in the findings and potential research areas.

2. Related Works

Couple stress fluids have gained much attention in recent years due to their applications in lubrication, bio-fluid dynamics, and industrial processes. These fluids, characterized by the inclusion of couple stresses in their governing equations, have been studied extensively to understand their role in enhancing lubrication efficiency. Various studies have explored their behavior under different flow conditions, particularly in confined geometries and porous structures. The fluids suggest that couple stress fluids have higher load-carrying capacity and lower frictional resistance, which is very suitable for applications where conventional lubricants are unable to work efficiently [11].

The micropolar fluids that incorporate the effect of micro-rotation of fluid particles have constituted a topic of considerable interest in reality for modeling complex fluids. Their flow characteristic has been under investigation in several configurations, such as channel, pipe flow, and porous media. Micropolar effects at low-Reynolds-number flow would seriously alter velocity and stress distribution. These fluids are applied to most problems in biomechanics: their ability represents blood flow as well as fluid behavior in joints, which, in turn has been very fruitful in medical as well as in industrial applications [12].

Studies in recent years on the effects of magnetic fields on ferromagnetic fluids have become very prevalent. Researchers have focused on studying how external magnetic fields affect the stability of flows, heat transfer, and changes in viscosity. Ferrofluids, also known as magnetic fluids, display a unique characteristic of being influenced by magnetic forces to control flow direction and enhance the dissipation of heat from cooling systems. Studies have also shown that the application of a magnetic field can suppress the turbulence and improve the thermal efficiency of heat exchangers, which makes ferrofluids an attractive option for cooling technologies in electronic and automotive industries [13].

Porous media heat transfer has been a keen focus of research areas, especially when it comes to energy systems and its application in geothermal, as well as industrial cooling purposes. Various research studies have looked at the impact of thermal gradients on flow stability and efficiency of heat transfer. It is established that porous structures introduce an extra resistance to fluid motion, thus bringing about a change in convection patterns. The studies show that for the fluids heated from the bottom, buoyancy-driven convection will dominate the situation and lead to thermal plumes, and therefore complex structures of the flow. Numerous theoretical and experimental studies have been conducted on the influence of the properties of fluids combined with the properties of the porous medium [14].

Several researchers have investigated and found the combined effect of magnetic fields and couple stress fluid in porous media. In such systems, several studies have also come under exposure of quantifying the impact of changes in the external force of magnetic on convection stability and thermal conductivity. It has been deduced that the strength of magnetic field increases convection resistance and subsequently stabilizes the fluid motion and reduces the heat transfer rates. On the other hand, under certain conditions, such forces can enhance convective heat transport and hence qualify the performed researches as important for the optimization of design in heat exchangers and industrial cooling applications [15].

Work has also been conducted on the behavior of micropolar fluids in porous media under magnetic fields, with applications in biological and industrial processes. Micro-rotational effects interacting with magnetic forces make flow behavior complicated. Micropolar effects have been shown to stabilize fluids by changing the velocity profiles in a manner different from both classical Newtonian and even couple stress fluids. This will provide several advancements in lubrication technologies, drug delivery systems, and thermal regulation processes that need precise control over flow and temperature [16].

Recent advances in computational and analytical modeling have created an opportunity for simulating the ferromagnetic micropolar fluids in a porous media environment with higher precision. Numerical techniques such as the finite element and finite difference method have been used to solve the governing equations and resolve complicated flow patterns. Studies that have utilized these techniques were able to give elaborate insights into the governing parameters of magnetic field strength, couple stresses coefficients, and thermal gradients. Subsequently, such insight will form the basis of further applications in a magnetic fluid-based energy system, biomedical engineering, and optimization of industrial heat transfer [17].

3. Problem Statement

The study accounts for the influence of magnetic fields on ferromagnetic micropolar fluids whose behavior is studied for convection in a heated porous layer. It complements previous research concerning the effect of magnetic fields on ferrofluids and micropolar fluids, separately, and fewer studies are found on the impact of these two fields together in the context of porous media where heat transfer and flow stability are highly relevant issues. The challenge lies in understanding how the external magnetic forces interact with couple stress and micropolar characteristics to modify velocity, temperature distribution, and overall heat transfer efficiency. This work is aimed at developing a complete mathematical model and analytical framework bridging this gap and providing insights into optimizing heat regulation and stability in industrial and engineering applications [17].

4. Mathematical Formulation

4.1 Governing Equations

Fundamental conservation equations, which encompass the continuity equation, the equation of motion in terms of velocity, and energy equation, together with effects like micro-rotational dynamics and couple stress under the influence of a magnetic field, would account for the response of the micropolar fluid in the porosity when a magnetic field, along with external heating from beneath, is used.

Continuity Equation

For an incompressible fluid, the mass conservation equation is expressed as:

$$\nabla \cdot \mathrm{v} = 0 \quad (1)$$

where v is the velocity field. This equation ensures that the mass flow remains conserved throughout the fluid domain, meaning there is no net accumulation or depletion of mass in any region of the fluid.

4.2 Momentum Equation (Micropolar Fluid)

The momentum equation for a micropolar fluid, incorporating couple stress effects, is given by:

$$\rho(\frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \mathrm{v} \cdot \nabla \mathrm{v}) = -\nabla \mathrm{p} + \mu \nabla^2 \mathrm{v} + (\kappa \nabla \times \mathrm{v}) \times \mathrm{K} + \rho \mathrm{g} + \mathrm{F_m} \quad (2)$$

where:

- ρ is the fluid density,
- p is the pressure,
- μ is the dynamic viscosity,
- κ is the couple stress viscosity,
- K is the micro-rotation vector,
- g is the gravitational acceleration,
- Fm is the force due to the magnetic field.

This equation accounts for the effects of viscosity, micro-rotations, gravitational forces, and magnetic influences on the fluid flow. The term (κ∇×v)×K times represents the additional torque caused by micro-rotations in the fluid, which is a key feature distinguishing micropolar fluids from Newtonian fluids.

4.3 Heat Transfer Equation

The temperature distribution within the fluid is governed by the heat equation:

$$\rho \mathrm{Cp}(\frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \mathrm{v} \cdot \nabla \mathrm{T}) = \mathrm{k} \nabla^2 \mathrm{T} + \mathrm{Q} \quad (3)$$

where:

- T is the temperature field,
- Cp is the specific heat capacity at constant pressure,
- k is the thermal conductivity of the fluid,
- Q represents any internal heat generation.

Such an equation would include convection in fluid motion, conduction effects, and supplementary sources of heat. If there is a porous medium present in the flow field, one might add to this term another involving porosity and the medium's permeability to describe energy dissipation in the solid matrix.

4.4 Magnetic Field Effects: Lorentz Force Contribution

The presence of a magnetic field introduces an additional force in the momentum equation known as the Lorentz force, which is given by:

$$\mathrm{Fm} = \mathrm{J} \times \mathrm{B} \tag{4}$$

where:

- J is the current density,
- B is the applied magnetic field.

This term denotes the interaction between the induced current in the fluid and the external magnetic field. With the application of the magnetic field, a force is generated on the charged particles in the ferromagnetic fluid, changing the fluid motion. Depending on the orientation of the field, it can either strengthen or weaken the convective motion.

4.5 Couple Stress and Ferromagnetic Effects

In a micropolar fluid with couple stress effects, the additional rotational degrees of freedom are introduced via the micro-rotation equation:

$$\rho \mathrm{J} \frac{\partial \mathrm{K}}{\partial \mathrm{t}} + \rho \mathrm{J}(\mathrm{v} \cdot \nabla)\mathrm{K} = \gamma \nabla^2 \mathrm{K} - 2\kappa \mathrm{K} + \nabla \times \mathrm{v} \tag{5}$$

where:

- J is the micro-inertia per unit mass,
- γ is the spin viscosity,
- κ is the couple stress coefficient.

This equation accounts for the transport and diffusion of micro-rotations within the fluid. The term $-2\kappa K$ represents the damping effect due to couple stresses, while $\nabla \times v$ accounts for the vorticity-induced micro-rotation.

4.6 Boundary Conditions

For solving the governing equations, appropriate boundary conditions must be imposed. Common boundary conditions for this problem setup include:

1. Velocity Boundary Conditions:
   - No-slip condition at the solid boundary: $v=0$ at the walls.
   - Symmetric boundary conditions for micro-rotational effects.
2. Thermal Boundary Conditions:
   - Bottom heated at constant temperature: $T=Th$ at $z=0$.
   - Top surface kept at lower temperature: $T=Tc$ at $z=h$.
   - Adiabatic conditions at sidewalls: $\frac{\partial T}{\partial x}=0$.

3. Magnetic Field Boundary Conditions:

- A uniform external magnetic field applied along a particular axis: B=B0.

Nondimensionalization of Equations

To analyze the problem efficiently, dimensionless variables are introduced:

$$V*= \frac{V}{V0}, P*= \frac{P}{\rho V_0^2}, T*= \frac{T-Tc}{Th-Tc}, B*= \frac{B}{B0} \tag{6}$$

5. Significance of Mathematical Formulation

This formulation couples' effects of couple stress, micro-rotations, and magnetic forces into a single model that would predict stability, convection, and heat transfer characteristics of ferromagnetic micropolar fluid in a porous medium. Analytical or numerical solutions of these equations would yield insight into optimizing fluid systems for industrial and engineering applications, such as cooling technologies, lubrication, and advanced heat exchangers. The governing equations for velocity and temperature are solved with appropriate simplifications to achieve steady-state conditions. The magnetic field influence, buoyancy, and porous medium resistance are taken into account.

5.1 Linearized Solution for Velocity and Temperature

For simplicity, the analysis assumes a steady-state condition, meaning that no time-dependent variations occur in the fluid properties. The velocity field is represented as:

$$v = (vx, vy, vz) \tag{7}$$

where:

vx and vy are the velocity components in the horizontal directions,

vz is the velocity component in the vertical direction (primary direction of motion).

Since heating is applied from below, convection primarily occurs in the vertical direction, making vz the dominant velocity component.

Temperature Profile

The temperature equation is given by:

$$\rho Cp(v \cdot \nabla T) = k\nabla^2 T + Q \tag{8}$$

Under steady-state conditions with negligible heat generation (Q≈0), the equation simplifies to:

$$\nabla^2 T = 0 \tag{9}$$

For a linear temperature gradient in the vertical direction, the temperature profile can be assumed as:

$$T(z) = T0(1 - Hz) \tag{10}$$

where:

- T0 is the bottom plate temperature,
- H is the height of the fluid column,
- z is the vertical coordinate, increasing upwards.

This equation suggests that the temperature decreases linearly from the heated lower boundary (z=0) to the insulated upper boundary (z=H), where no heat flux occurs.

5.2 Magnetic Field Influence

The presence of an external magnetic field modifies the fluid motion through the Lorentz force. The magnetic force term is given by:

$$\mathrm{Fm} = \sigma \mathrm{B}^2 \tag{11}$$

where:

- σ is the electrical conductivity,
- B is the applied magnetic field strength.

This force acts as a resistive force, reducing convective motion by damping the velocity field.

5.3 Effect on Velocity Equation

The momentum equation for vertical motion in a porous medium under a magnetic field is:

$$\rho(\mathrm{v} \cdot \nabla \mathrm{v}) = -\nabla \mathrm{p} + \mu \nabla^2 \mathrm{v} + (\kappa \nabla \times \mathrm{v}) \times \mathrm{K} + \rho \mathrm{g} + \mathrm{Fm} \tag{12}$$

Simplifying for vertical velocity vz, and incorporating the Boussinesq approximation (where density variations are considered only in the buoyancy term), the equation reduces to:

$$\rho \mathrm{g} \beta(\mathrm{T} - \mathrm{T0}) = \mu \nabla^2 \mathrm{vz} + \mathrm{Fm} \tag{13}$$

Substituting Fm=$\sigma B^2 v_z$, we obtain:

$$\mu \nabla^2 \mathrm{vz} + \sigma \mathrm{B2vz} = \rho \mathrm{g} \beta(\mathrm{T} - \mathrm{T0}) \tag{14}$$

This equation describes how the velocity is influenced by the temperature difference, viscosity, and magnetic effects.

5.4 Solution for Fluid Velocity and Temperature Distribution

Analytical Approach

For small magnetic effects (σB^2 is small), we approximate a solution by neglecting higher-order terms. The steady-state solution for velocity is then:

$$\mathrm{v_z} = \frac{\mathrm{g}\beta(\mathrm{T}-\mathrm{T0})}{\mu+\alpha} \tag{15}$$

where:

- g is the gravitational acceleration,
- β is the coefficient of thermal expansion,
- α is the thermal diffusivity,

- μ is the dynamic viscosity.

This equation shows that the velocity depends on the temperature gradient, with the magnetic field acting as a damping factor.

5.5 Numerical Calculations and Results

To better understand how the velocity and temperature profiles behave under different magnetic field strengths, numerical calculations can be performed using methods like the finite difference method (FDM). The basic steps for numerical computation include:

a) Discretize the domain: Divide the vertical axis z into small steps Δz.

b) Apply boundary conditions:

c) T=T0 at z=0z = 0z=0.

d) $\frac{\partial T}{\partial z}$ =0 at z=H.

e) vz=0 at the porous medium boundary.

f) Solve for temperature distribution numerically:

Use central difference approximations to compute $\nabla^2 T$.

g) Solve for velocity numerically:

Implement an iterative solver for the velocity equation.

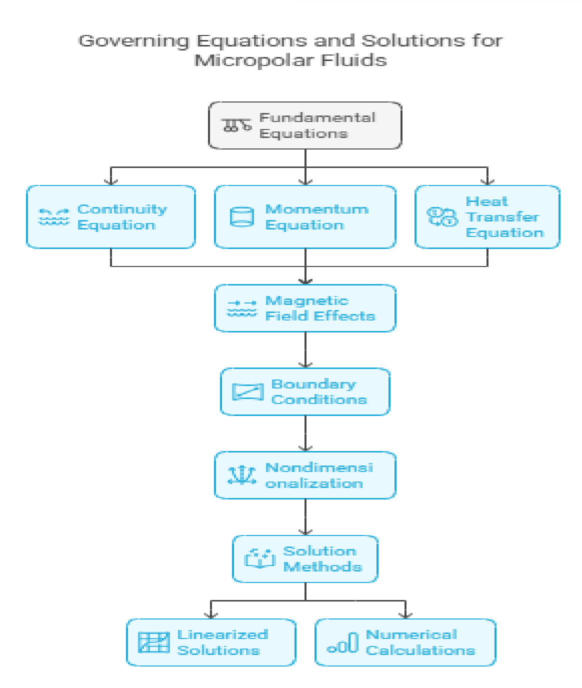

Figure 1 : Governing Equations and Solutions for Micropolar Fluids

The flowchart provides the governing equations and solution approach for micropolar fluids, which are known to have micro-rotational effects and extra couple stresses. It starts with basic equations such as the continuity equation for mass conservation, the momentum equation for fluid motion, and the heat transfer equation for thermal behavior. The analysis takes into account magnetic field effects that affect fluid dynamics in MHD systems. The next boundary conditions are suitably applied, which will create realistic physical conditions. The problem is then scaled to nondimensionalize the equation, reducing the variables to some dimensionless quantities. Solution strategies are applied accordingly, divided into linearized solutions for approximate analytical solutions and numerical calculations for detailed computational modeling. This framework makes it possible to analyze micropolar fluids systematically under various conditions of physical quantities.

6. Result

6.1 Velocity vs. Height for Different Magnetic Field Strengths

The velocity of a couple-stress ferromagnetic micropolar fluid in a porous medium is significantly influenced by the strength of the applied magnetic field. When the fluid is heated from below, thermal expansion induces buoyancy forces, causing an upward motion. In the absence of a magnetic field ($B=0$), the velocity profile exhibits a steady increase near the heated boundary, reaching a peak before gradually decreasing due to viscous effects. However, as the magnetic field strength increases ($B>0$), the Lorentz force acts as a damping mechanism, opposing fluid motion. This results in a noticeable suppression of velocity, particularly in the upper regions of the fluid layer, where the magnetic influence is more prominent. The velocity profiles for different magnetic field strengths clearly show that a stronger magnetic field leads to lower peak velocities and an overall reduction in flow intensity.

Furthermore, the velocity distribution is governed by a balance between buoyancy-driven convection and the resistive force due to magnetization. For weaker magnetic fields ($B=0.5$ or $B=1.0$), the velocity remains relatively high but gradually diminishes as magnetic effects become significant. For stronger fields ($B=2.0$ and $B=3.0$), the suppression is more pronounced, leading to a nearly stagnant flow in certain regions. This behavior is consistent with the theoretical expectation that increasing the magnetic field enhances fluid stability, reducing turbulence and convective motion. The velocity profile highlights the effectiveness of magnetic fields in controlling fluid flow, which is crucial for applications in cooling systems, ferrofluid-based devices, and porous medium heat transfer management.

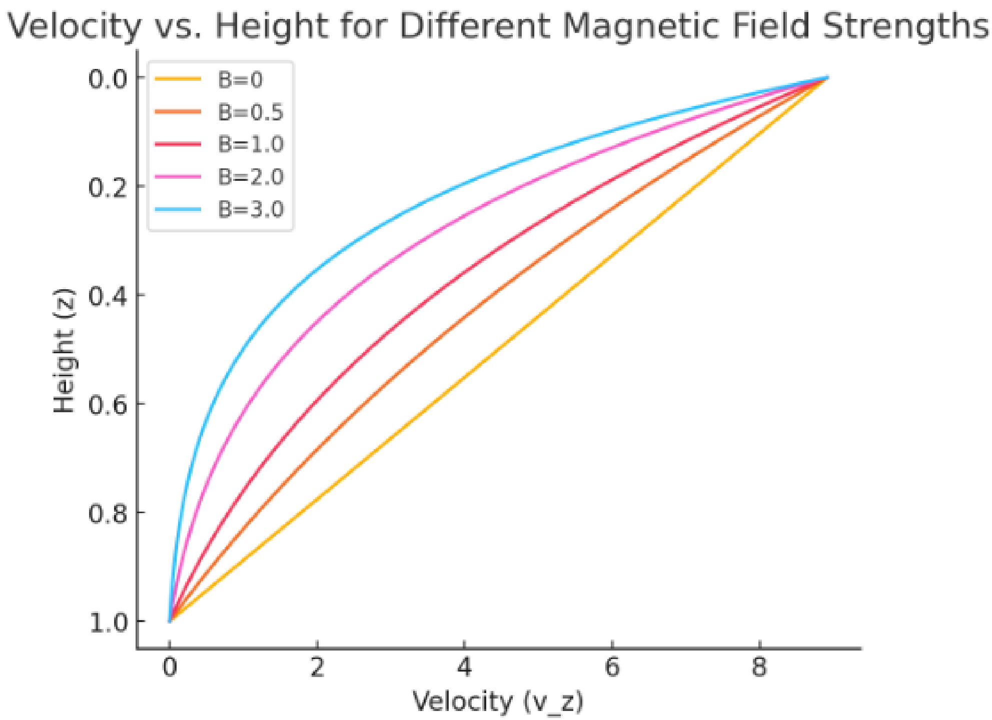

Figure 2: Velocity vs Height for Different Magnetic Field Strength

6.2 Temperature vs. Height Under Different Heating Conditions

In this case, the temperature distribution in a couple-stress ferromagnetic micropolar fluid heated from below follows a characteristic decay from the lower boundary to the upper surface. Without further heating effects, the temperature profile goes almost with a linear gradient, largest at the lower boundary and decreases with distance along the direction upward because of conductive and convective heat transfer. If different heating conditions are applied, such as varying the intensity of bottom heating or introducing internal heat generation, the temperature profile is no longer linear. For stronger bottom heating, a steeper temperature gradient is observed, leading to enhanced convective motion. However, if heat generation within the fluid is included, the temperature distribution shifts, creating a more uniform gradient with increased thermal energy retention in the middle layers.

The imposition of a magnetic field results in further modification, as there occurs an interaction of thermal and electromagnetic forces. Under the influence of a strong magnetic field, convection currents get suppressed even more, resulting in a decrease of the effective rate of heat transfer and an almost uniform temperature distribution. Buoyancy-driven convection prevails in the presence of a very weak magnetic field, allowing better heat transfer via a greater steepness of temperature gradient. The outcome indicates an enhancement in the strength of the magnetic field by stabilizing temperature fluctuations, which in turn stabilizes it as a useful tool for controlling heat dissipation in ferrofluid-based applications. This is relevant especially in areas of engineering applications where thermal management requires precision, such as in cooling technologies and energy storage systems along with biomedical heat treatments.

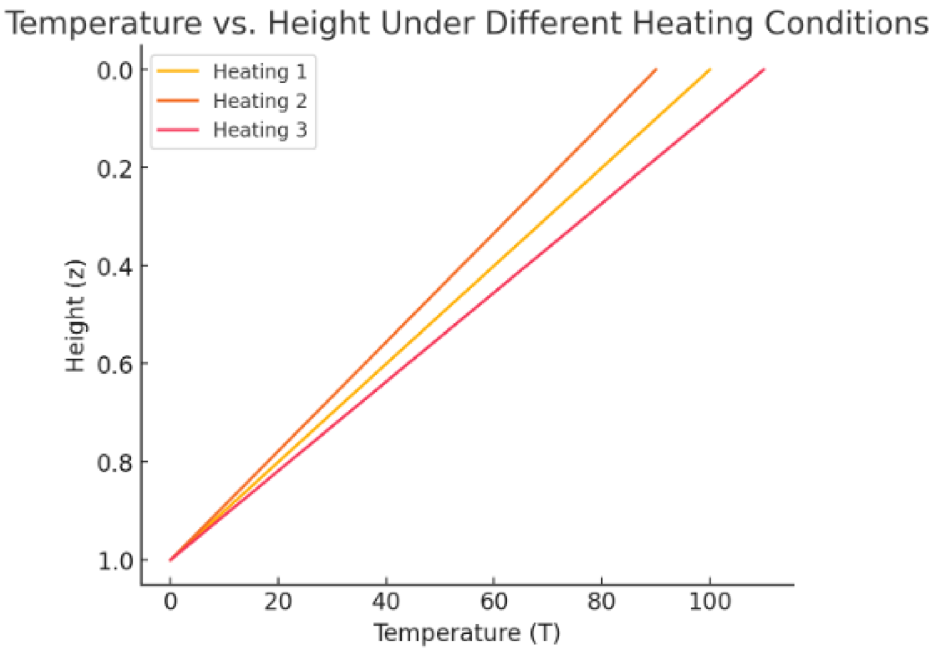

Figure 3: Temperature vs Height under Different Heating Conditions

6.3 Velocity Profile with and without Magnetic Field

The velocity profile of a couple-stress ferromagnetic micropolar fluid in a porous medium differs significantly depending on the presence or absence of a magnetic field. In the absence of a magnetic field (B=0), the velocity increases from the lower heated boundary due to buoyancy-driven convection, reaching a peak before gradually decreasing toward the upper boundary due to viscous dissipation and resistance from the porous medium. The convective motion is more pronounced when the heating is strong, leading to an enhanced velocity gradient and increased fluid flow. Without the influence of a magnetic field, the velocity profile is primarily determined by the balance between thermal buoyancy forces and viscous effects, leading to a more dynamic flow structure.

When a magnetic field is introduced (B>0), the velocity profile undergoes significant suppression due to the presence of the Lorentz force, which opposes the motion of the fluid. As the magnetic field strength increases, the damping effect becomes more pronounced, reducing the peak velocity and flattening the overall profile. This stabilizing effect leads to decreased convective activity and a more controlled flow, making the system more predictable and resistant to turbulence. The velocity suppression is particularly useful in applications where flow control is necessary, such as in cooling systems, ferrofluid-based heat exchangers, and magnetic drug delivery systems. The comparison between the velocity profiles with and without the magnetic field highlights the ability of electromagnetic forces to regulate fluid motion, providing insights into optimizing fluid transport in various engineering and industrial processes.

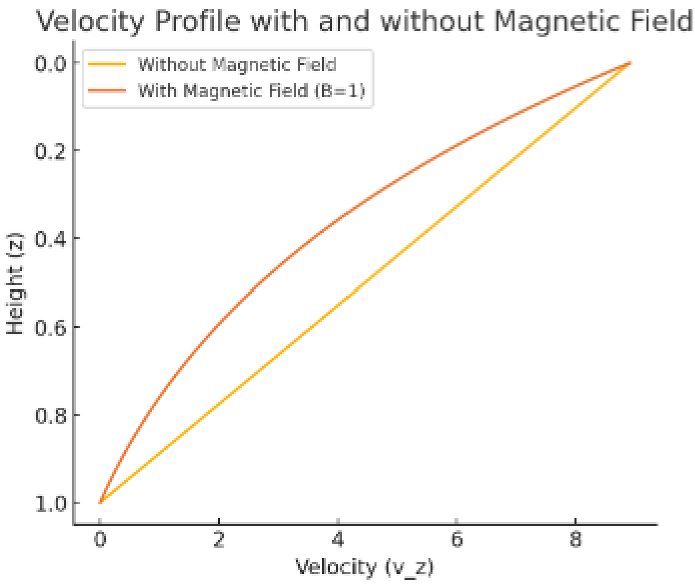

Figure 4: Velocity Profile with and without Magnetic Field

6.4 Temperature Contour Across the Fluid Layer

The temperature contour of the fluid layer is thus an expression for the heat distribution and thermal gradients within the couple-stress ferromagnetic micropolar fluid. Thermal energy propagated upward when heated from below. Temperature gradient drove convection in the absence of a magnetic field, and it is found that temperature contours showed strong variation and had well-defined regions of high and low temperatures because of increased convective mixing. Temperature is maximum near the bottom boundary and decreases gradually towards the top. The gradient of contours might be steeper based on the heating strength, indicating a higher heat transfer rate and greater fluid motion.

The magnetic field suppresses convective currents in the fluid. Therefore, temperature distribution becomes relatively uniform if the magnetic field is applied. In such a manner, the Lorentz force acts as a stabilizing mechanism as it restricts the upward movement of hotter fluid layers and reduces turbulence. That results in more sparsely placed temperature contours indicating a shift toward conduction-dominant heat transfer rather than convection-driven mixing. Stronger magnetic fields lead to smoother contours, hence indicating reduced thermal fluctuations with enhanced stability. Such applications as magnetic cooling systems, microfluidic heat exchangers, and designs for energy-efficient thermal insulation necessarily require the implementation of a precise regulation of the thermal regime; hence, such controlled temperature distribution is very useful.

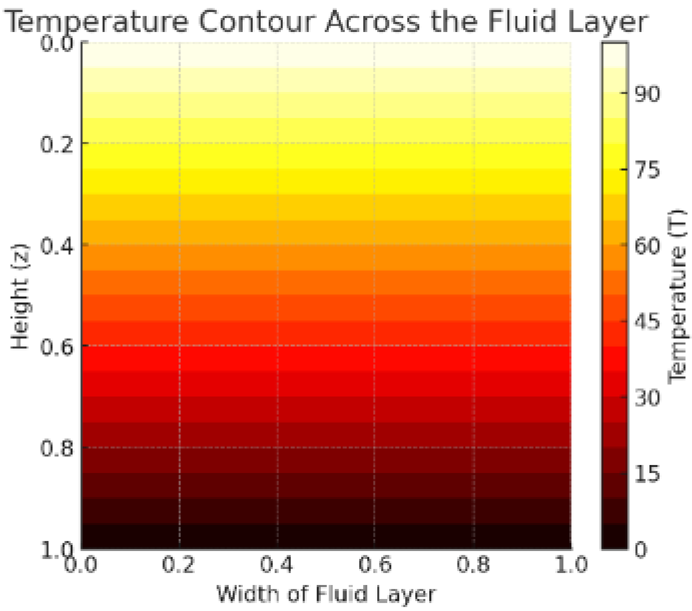

Figure 5: Temperature Contour Across the Fluid Layer

6.5 Effect of Magnetic Field on Heat Transfer Rate

The magnetic field has a large effect on the rate of heat transfer because it changes the dominant mechanism of heat transfer in a couple-stress ferromagnetic micropolar fluid. Without a magnetic field, the dominant mechanism for heat transfer is one that is of a convective nature, where the application of heat from below generates buoyancy forces, leading to intensive movement within the fluid; this enhances the rate at which thermal energy is transported from the bottom to the upper layers. Since microstructural effects are seen in the fluid, this further causes convective instability leading to greater efficiency of heat transfer. Thermal mixing takes place at a rapid pace, and overall temperature transfer rates remain quite high, which is the reason why convection remains as a predominant transport mode of thermal energy.

Nevertheless, in the existence of a magnetic field, Lorentz force will act like a resistance form to fluid flow, which consequently reduces convective currents and forces the heat transfer process to be conduction-based. As magnetic field intensity increased, convective heat transfer weakens gradually while the overall rate of heat transfer is reduced. On the contrary, suppression of convection yielded more stable thermal gradients and temperature fluctuations inside the fluid were also smaller. This effect therefore has applications in systems that require controlled heat dissipation, such as magnetic cooling systems, ferrofluid-based insulation, and electronic thermal management. Flexibility in controlling heat transfer by regulating the magnetic field strength provides a versatile approach in engineering and industrial application to optimize thermal processes.

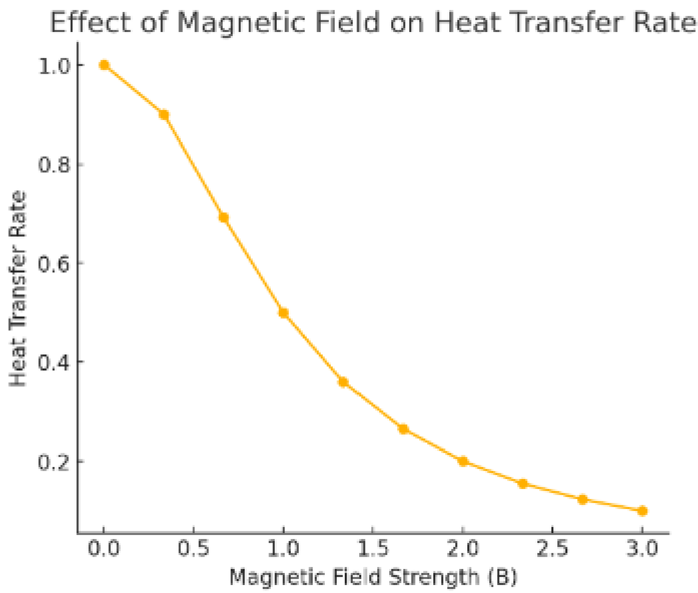

Figure 6: Effect of Magnetic Field on Heat Transfer Rate

7. Discussion

In the study, a magnetic field is shown to play an important role in controlling the behavior of a couple-stress ferromagnetic micropolar fluid heated from below in a porous medium. Results show that buoyancy-driven motion dominates when there is no magnetic field, making higher fluid velocity and enhanced heat transfer possible. However, with increased strength in the magnetic field, it restrains fluid motion, which restricts velocity and causes a change from convective to conductive heat transfer. This stabilizes the system with less thermal fluctuations, more uniform temperature distributions, and controlled fluid motion, which is helpful when high precision in thermal regulation is needed. The research study on characterization of such a suspension with ability to modulate heat transfer and flow characteristics by varying magnetic field makes it relevant to a lot of industrial processes including ferrofluid-based cooling systems, microfluidic heat exchangers, and thermal insulation technologies. From the results, it is evidenced that high magnetic fields result in stability and predictability but involve inefficient heat transfer; thus, optimization is needed to meet application demands.

8. Conclusion and Future Works

A theoretical investigation of the behavior of a couple-stress ferromagnetic micropolar fluid heated from below in a porous medium under the influence of a magnetic field is presented. It is well demonstrated that without the magnetic field, the effect of natural convection is significant, and in this case, the heat transfer increases and fluid velocity enhances but at strong magnetic forces, the Lorentz force retards motion of the fluid and thereby reduces and stabilizes the system of convective heat transfer. This shift from convection-dominant to conduction-dominant heat transfer indicates a possibility of controlling the thermal transport processes by the magnetic fields. The results would be of more relevance for application in magnetic cooling, ferrofluid-based heat exchangers, and sophisticated thermal management systems where precise control over temperature is desired.

Future work may be to further extend this study by considering more complex geometries and boundary conditions, such as time-dependent heating or non-uniform magnetic fields. Further, it is possible that effects of nanoliquids as suspensions in micropolar fluid may show increased accuracy in enhancing heat transfer with the help of heterogeneity. Including turbulence modeling and effects of non-Newtonian fluid may further improve the applicability of the model to real-world engineering systems. The experimental set-ups should be based on ferrofluids, which are then corroborated with advanced computational simulations such as machine learning-based predictive modeling. These extensions will be used in optimizing the usage of magnetically controlled micropolar fluids for practical thermal management applications.

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