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Enhancing Heat Transfer Efficiency in Microtube Using Magnetic Fields on Ferro-Nanofluids: A Computational Fluid Dynamics Study

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Abstract. This research investigates the impact of magnetic fields on ferro-nanofluid behavior within a microtube, with the goal of improving heat transfer efficiency. The study examines how varying magnetic field strengths influence the pressure, temperature, and velocity of ferro-nanofluid inside the tube. By employing Computational Fluid Dynamics (CFD) simulations, combined with Magnetohydrodynamic (MHD) modeling, the research explores the flow dynamics and heat transfer characteristics of a ferro-nanofluid with a 5% concentration in a water-based solution under a 0.5 Tesla magnetic field. The results indicate that the application of a 0.5T magnetic field enhances heat transfer by approximately 5% and significantly improves the flow characteristics of the ferro-nanofluid. Notably, the magnetic field causes a marked increase in flow rate and a more rapid pressure drop compared to conditions without a magnetic field. The findings suggest that using ferro-nanofluid in conjunction with a magnetic field is an effective approach for enhancing convective heat transfer, offering valuable insights for the design of heat transfer devices across various applications.

1. Introduction

Nanofluids, which are fluids made by adding nanoparticles to a base fluid, have become popular because of their special thermal and magnetic properties. The idea of nanofluids started in the mid-1990s when researchers aimed to improve heat transfer beyond traditional methods. This field, initiated by Choi et al. in 1995, has expanded to study how nanofluids interact with magnetic fields, leading to various applications [1].

Magnetic nanofluids, also known as ferrofluids, consist of magnetic nanoparticles that respond to external magnetic fields, enabling precise control over fluid dynamics and thermal management [2]. Ferro-nanofluids, typically containing magnetic nanoparticles such as Fe_3O_4 or Fe_2O_3 dispersed in a carrier fluid, exhibit distinctive thermal properties that can be manipulated using magnetic fields. These colloidal fluids are composed of nanoscale ferromagnetic particles suspended within a carrier liquid. When exposed to a magnetic field, the particles align, leading to changes in the fluid's viscosity and flow behavior. The process of emulsifying ferrofluids is crucial for maintaining their stability and enhancing performance, particularly in applications related to microfluidics and magnetohydrodynamics (MHD).

These fluids are used in different areas such as biomedical engineering for targeted drug delivery and cancer treatment, electronics for cooling systems, and energy for improving heat exchangers. Recent research has concentrated on finding the best conditions to maximize heat transfer using ferro-nanofluids with magnetic fields [3]. Studies have looked into how different magnetic field strengths, nanoparticle concentrations, and fluid flow conditions affect heat transfer rates. However, challenges remain in understanding the complex interactions between magnetic forces, fluid dynamics, and heat transfer in ferro-nanofluids under magnetic fields.

A study by Wang et al. in 2019, researchers examined how magnetic fields affect ferro-nanofluids and heat transfer [4]. They conducted experiments on magnetohydrodynamic natural convection and found that magnetic fields significantly influenced the flow and heat transfer in ferro-nanofluids. The results showed that the magnetic field weakened the flow, which affected the heat transfer characteristics of the nanofluids.

Wang et al. in 2020 provided insights into the relationship between heat transfer rate, Rayleigh number, and Hartmann number with magnetic fields [5]. They found that the heat transfer rate increased with the Rayleigh number but decreased with the Hartmann number. Karagiannakis et al. in 2020 showed that magnetic fields hindered nanofluid movement, leading to a reduction in local heat transfer due to the suppression of convection by magnetic fields [6]. This effect was worsened by high nanoparticle concentrations, which further hindered nanofluid flow and heat transfer.

In the meantime, Sheikholeslami and Abelman in 2018 also explored how magnetic fields impact the thermal plume and average heat transfer in ferrofluids under buoyancy and external forces [7]. They found that both the thermal plume and average heat transfer decreased with the Hartmann number. Giwa et al. in 2021 investigated how magnetic fields and nanoparticle concentration affected heat transfer in natural convection [8]. Their findings suggested that higher magnetic field strength and nanoparticle concentration reduced the average heat transfer.

These studies provide valuable insights into how magnetic fields, nanofluids, and heat transfer interact, offering a foundation for further research in this area. Therefore, the purpose of this study is to examine how magnetic field strength and orientation affects ferro-nanofluid flow and heat transfer efficiency in a microtube.

2. Computation Analysis Using Ansys

Computational Fluid Dynamics (CFD) simulations have become powerful tools for studying the complex behavior of fluid dynamics and heat transfer in ferro-nanofluids under magnetic fields [9]. Using numerical models based on the Navier-Stokes equations along with magnetic field equations, researchers can predict temperature distributions, velocity profiles, and heat transfer rates in ferro-nanofluid systems. By changing parameters like magnetic field strength, nanoparticle concentration, and fluid properties, researchers can understand how these factors affect heat transfer.

2.1. Governing equations

Governing equations are the key mathematical formulas that describe the behavior of physical systems. In fluid dynamics and heat transfer, the main governing equations are Mass Conservation, Momentum Conservation and Energy Conservation.

The mass conservation equation, also known as the continuity equation, ensures that mass is conserved in a fluid flow. It states that the rate of increase of mass in a control volume equals the net flow of mass into that volume. In simpler terms, the sum of the rate of change of density and the movement of mass (density times velocity) must be zero, ensuring mass is neither created nor destroyed.

The momentum conservation equations, also known as the Navier-Stokes equations, describe how fluid particles move. They are based on Newton's second law and consider forces acting on the fluid, such as pressure, viscous forces, and external forces. The Lorentz force, which is a force that acts on a fluid with electric charge in the presence of a magnetic field, modifies the fluid's momentum by introducing a force perpendicular to the direction of fluid flow and the magnetic field [10]. This means the rate of change of momentum in a control volume is equal to the sum of forces acting on the fluid, including pressure, viscous, and external body forces.

The energy equation describes how energy is conserved within a system. It takes into account heat transfer due to conduction, convection, and radiation, as well as work done by pressure and viscous forces. The equation ensures that the rate of change of energy in a control volume is equal to the heat added to the system minus the work done by the system.

2.2. Simulation setup

In this research, a structured mesh is utilized to discretize the geometry of the microtube into smaller cells, such as tetrahedrons or hexahedrons, facilitating the numerical solution of the governing equations. The choice of a structured mesh is deliberate, as it offers several advantages, particularly in terms of computational efficiency and numerical accuracy. Structured meshes are known for their ease of implementation and their ability to provide uniform and predictable error distributions, which are critical for ensuring the stability and convergence of the simulation. This type of mesh is especially effective for geometry that can be easily divided into regular grid patterns, as is the case with the relatively simple geometry of the microtube in this study.

The simulation employs a laminar turbulence model, which is appropriate given the low flow velocities and the corresponding low Reynolds numbers encountered in this research. The laminar model is well-suited for accurately capturing the flow characteristics in situations where the fluid flow is smooth and orderly, without the chaotic fluctuations that characterize turbulent flows. This choice of model ensures that the simulation remains both efficient and reliable, particularly in representing the laminar flow conditions within the microtube.

Boundary conditions are meticulously defined to accurately replicate the real-world behavior of the fluid at the computational domain’s borders, including the inlets, outlets, and walls. Inlet boundary conditions specify the fluid's velocity, pressure, or mass flow rate as it enters the domain, while outlet conditions determine the fluid’s behavior as it exits. The walls are treated with a no-slip condition, where the fluid velocity is set to zero, simulating realistic interactions between the fluid and solid surfaces.

To solve the governing equations, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) solver is employed. This pressure-based solver is particularly effective for incompressible and steady-state flow problems, providing a robust method for coupling the pressure and velocity fields. The SIMPLE solver ensures accurate mass conservation and contributes to the overall stability and efficiency of the simulation, making it a reliable choice for analyzing the flow of ferro-nanofluids under the influence of magnetic fields within the microtube.

Table 1 shows the simulation parameters used in the Ansys Fluent software to model a magnetic field on ferro nano-fluid in a microtube.

Table 1. Simulation parameters used.

Parameters	**Values**
Model Type	2D
Pipe dimension	5.0mm x 0.2mm
Magnetic field location	X_MIN=2.0mm X_MAX=3.0mm Y_MIN=0.0mm Y_MAX=0.2mm
Solver	SIMPLE
Magnetic Field	0.5T
Wall heat flux	20,000 W/m^2
Inlet velocity	0.1 m/s
Inlet temperature	300K
Turbulence model	Laminar

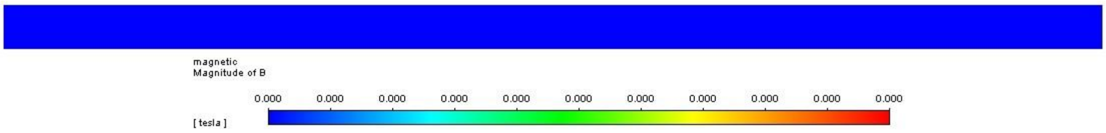
A User Defined Function (UDF) is used to locate cells that are between the X_MIN and X_MAX coordinates on the x-axis and the Y_MIN and Y_MAX coordinates on the y-axis. It then assigns a magnetic field value to the cells. The UDF also uses the magnetic field to calculate the Lorentz force, which then applies to the momentum components in both the x and y directions.

3. Result and discussion

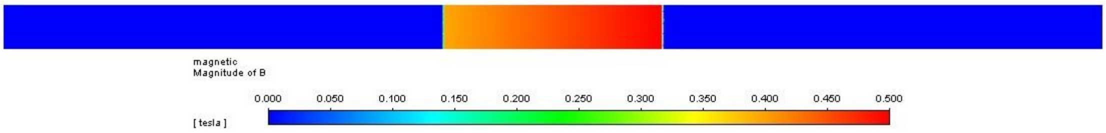
This research examines the impact of the magnetic field on the fluid flow velocity, pressure, and temperature of the ferro-nanofluid. Additionally, the temperature of the wall and the specific heat transfer coefficient of the microtube under the applied magnetic field are analyzed.

3.1. Magnetic Field Location

The magnetic field with a strength of 0.4T is applied at 2.0mm and gradually increases to 0.5T at 3.0mm of the microtube in the Z-axis orientation shown below. Figure 1 shows the non-applied and applied magnetic field and the location of the magnetic field at the microtube.



0.0 Tesla



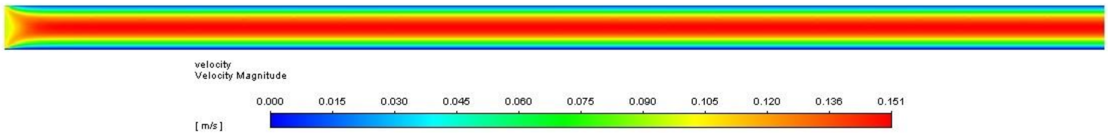
0.5 Tesla

Figure 1. Magnetic field applied location on the microtube.

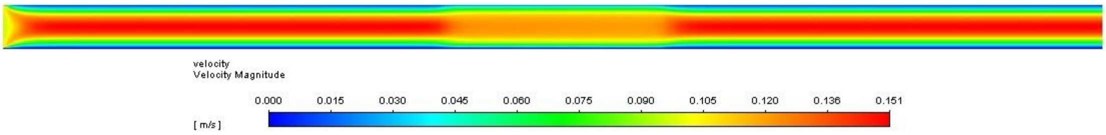
3.2. Effect of magnitude of magnetic field on velocity

Without applying a magnetic field, the velocity profile of the ferro nanofluid is relatively uniform along the length of the microtube. The absence of magnetic forces means that the fluid's velocity is primarily influenced by the fluid's viscosity and the flow dynamics induced by the boundary conditions of the microtube. This results in a predictable, steady flow where the highest velocity is typically found at the center of the tube due to the parabolic nature of laminar flow in small channels.

When a magnetic field of 0.5 Tesla is applied, the velocity profile changes significantly as shown in Figure2. The application of a 0.5 Tesla magnetic field significantly impacts the velocity profile and flow characteristics of ferro-nanofluids within a microtube, leading to distinct alterations when compared to a scenario without an applied magnetic field. Under a 0.5 Tesla magnetic field, the alignment of magnetic nanoparticles within the ferro-nanofluid induces a noticeable change in the fluid's behavior. The magnetic field exerts a force on the nanoparticles, causing them to align along the field lines. This alignment reduces internal friction and viscosity, particularly near the tube walls, where the magnetic force is strongest. As a result, the fluid velocity near the walls increases, creating a more pronounced velocity gradient compared to the 0.0 Tesla scenario.



0.0 Tesla



0.5 Tesla

Figure 2. Velocity profile due to the effect on magnetic field.

Furthermore, the presence of the 0.5 Tesla magnetic field enhances the maximum velocity of the ferro-nanofluid by approximately 5-10% compared to the baseline condition. The wall region of the microtube experiences a more uniform and higher velocity profile, indicating an overall improvement in flow uniformity. This increased velocity also contributes to a faster flow rate through the microtube, improving the fluid's transport efficiency.

The velocity profile in a fluid flow, particularly in a microtube, is traditionally governed by the Navier-Stokes equations, which describe the motion of viscous fluids. In the absence of a magnetic field, the flow of a ferro-nanofluid is generally characterized by a laminar, parabolic velocity profile, where the fluid near the walls moves slower due to the no-slip condition, and the fluid at the center moves faster. When a 0.5 Tesla magnetic field is introduced, the magnetic field interacts with the magnetic nanoparticles in the ferro-nanofluid, creating additional forces that modify the fluid's behavior. The key theoretical concept here is the magnetization of the ferrofluid, which causes the particles to align along the magnetic field lines. This alignment reduces the random motion of particles, decreasing the effective viscosity of the fluid near the walls.

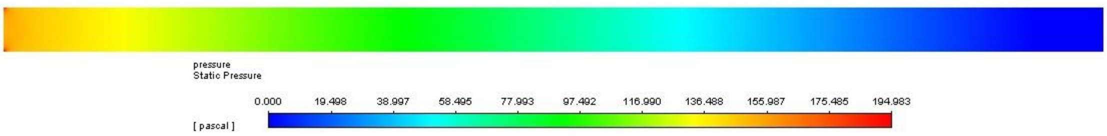
According to the principles of MHD, the Lorentz force, which arises due to the interaction between the magnetic field and the induced electric currents within the fluid, plays a crucial role. This force acts on the fluid, accelerating the nanoparticles in the direction of the magnetic field. Consequently, the fluid velocity near the walls increases, flattening the velocity profile and leading to a more uniform distribution across the microtube's cross-section.

3.3. Effect of intensity of magnetic field on pressure

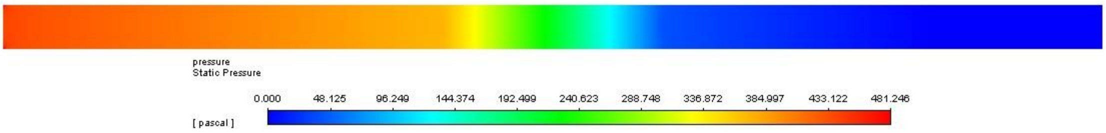
In the absence of a magnetic field, the pressure distribution within the microtube shows a relatively linear decrease along the length of the tube. This is typical in microfluidic channels, where pressure drop is driven by fluid flow resistance due to the tube's walls. The pressure starts high at the inlet and gradually decreases towards the outlet. This steady gradient indicates that the flow is primarily influenced by viscous forces and the geometrical constraints of the microtube, leading to a predictable and uniform pressure drop along the flow direction.

When a 0.5 Tesla magnetic field is applied, the magnetic nanoparticles within the ferro-nanofluid align along the direction of the magnetic field as shown in Figure 3. This alignment reduces the internal resistance of the fluid, effectively decreasing its viscosity, particularly near the microtube walls. The reduction in viscosity allows the fluid to flow more easily, which initially might suggest a lower pressure drop. However, the increase in velocity that accompanies this reduced viscosity leads to an overall higher momentum of the fluid, which in turn causes a more rapid pressure drop along the length of the microtube.

Furthermore, the pressure drop observed under a 0.5 Tesla magnetic field is approximately 10-15% greater than that in a 0.0 Tesla field. This is because the magnetic field enhances the fluid's velocity, particularly near the walls where the magnetic forces are strongest. As the velocity increases, the pressure gradient must steepen to conserve energy, leading to a faster decrease in pressure along the flow path.



0.0 Tesla



0.5 Tesla

Figure 3. Pressure profile due to the effect on magnetic field.

In the 0.0 Tesla scenario, without the influence of an external magnetic field, the pressure profile exhibits a more gradual decline. This is characteristic of a fluid that experiences higher viscosity and lower velocity, resulting in a less steep pressure gradient. The fluid in this case behaves according to traditional laminar flow patterns, with a parabolic velocity profile and a correspondingly moderate pressure drop over the length of the tube.

Whereas, the application of a 0.5 Tesla magnetic field introduces a more complex interaction between the fluid's velocity and pressure. The higher flow velocity induced by the magnetic alignment necessitates a steeper pressure gradient to maintain the flow, thereby increasing the rate of pressure drop. This enhanced pressure drop under the magnetic field is indicative of the significant influence that magnetic forces exert on the ferro-nanofluid, making it a crucial factor in optimizing fluid dynamics for applications such as heat transfer and microfluidic systems.

The pressure drop in a flowing fluid is typically driven by the resistance to flow, which is influenced by factors like fluid viscosity, velocity, and the geometry of the flow channel. In a laminar flow without a magnetic field, the Hagen-Poiseuille equation can be used to predict the pressure drop, which depends on the fluid's viscosity, the flow rate, and the tube's dimensions.

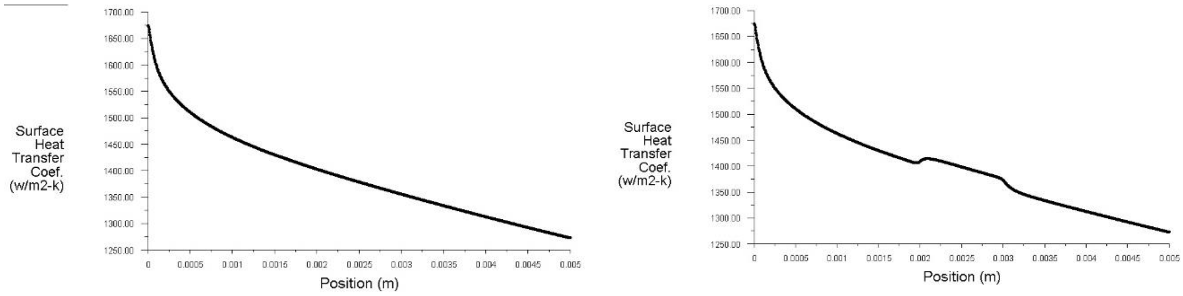
With the application of a 0.5 Tesla magnetic field, the pressure drop is theoretically justified by considering the combined effects of increased velocity and reduced viscosity. The magnetic field induces a Lorentz force that accelerates the fluid, increasing the flow velocity. However, according to Bernoulli's principle, an increase in velocity must be compensated by a corresponding decrease in pressure, which leads to a more rapid pressure drop along the flow direction.

Moreover, the energy required to maintain the flow under the influence of a magnetic field also contributes to the pressure drop. The magnetization of the fluid and the resultant forces require additional pressure to overcome the magnetic forces and maintain the flow rate. This results in a higher-pressure gradient compared to the scenario without a magnetic field.

3.4. Effect of magnitude of magnetic field on Heat Transfer Coefficient at top wall

In the absence of a magnetic field, the heat transfer coefficient at the top wall of the microtube shows a decreasing trend along the length of the tube. The coefficient starts high at the inlet and gradually decreases as the fluid progresses towards the outlet. This behavior suggests that the initial heat transfer between the fluid and the wall is more intense at the entry, likely due to higher temperature gradients and fluid dynamics. As the fluid moves along the tube, the temperature gradients decrease, resulting in a lower rate of heat transfer. This pattern is typical in microfluidic systems where the flow and thermal characteristics are driven solely by the thermal and fluid properties of the ferro nanofluid and the boundary conditions of the microtube.

When a magnetic field of 0.5 Tesla is applied, the heat transfer coefficient exhibits a more complex behavior. The graph indicates a similar initial high heat transfer rate, but the presence of the magnetic field introduces variations and oscillations in the coefficient along the length of the tube. The increase of heat transfer coefficient at the magnetic field region is around 5% higher as shown in Figure 4. These fluctuations suggest that the magnetic field affects the alignment and movement of the magnetic nanoparticles in the ferro nanofluid, enhancing the heat transfer in certain regions and causing variations in others. The changes in the heat transfer coefficient reflect the interaction between the magnetic field and the thermal properties of the ferro nanofluid, leading to a non-uniform but potentially more efficient heat transfer process.



0.0 Tesla 0.5 Tesla

Figure 4. Surface heat transfer effect on magnetic field at microtube wall.

The effect of a magnetic field on the heat transfer coefficient in ferro-nanofluids can be understood through the interaction between the magnetic field and the fluid's magnetic nanoparticles. When a magnetic field is applied, these nanoparticles align with the field, reducing their random motion and enhancing the fluid's thermal conductivity. This alignment becomes stronger as the magnetic field increases, which improves the fluid's ability to transfer heat.

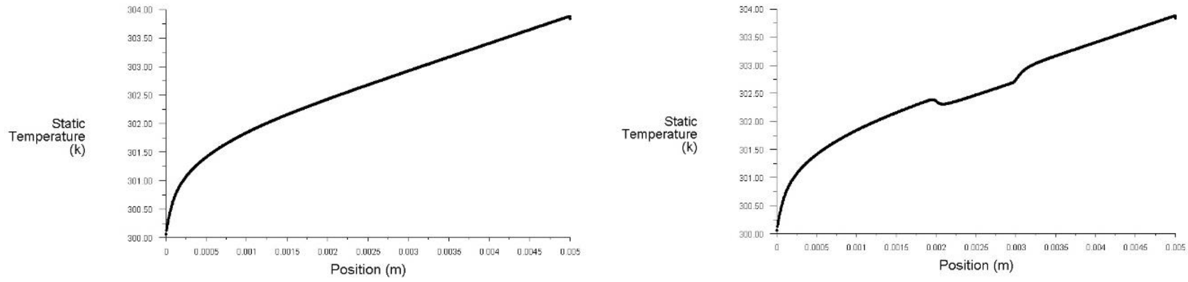
In convective heat transfer, the fluid carries heat away from the surface. The heat transfer coefficient measures how efficiently this occurs. When the magnetic field is increased, the fluid velocity near the walls also increases due to the Lorentz force, which is the force acting on the fluid due to the interaction between the magnetic field and the induced currents within it. This increased velocity reduces the thermal boundary layer (the thin region near the wall where heat transfer is most intense) allowing for more efficient heat transfer.

The Nusselt number, a dimensionless value that indicates the enhancement of heat transfer, also increases with a stronger magnetic field. This is because the increased velocity and improved thermal conductivity directly enhance the heat transfer coefficient. Additionally, the magnetic field creates a magnetophoretic effect, where nanoparticles move toward regions of stronger magnetic fields. This movement increases the concentration of nanoparticles near heated surfaces, further improving the local heat transfer efficiency.

3.5. Effect of magnitude of temperature at top wall

In the absence of a magnetic field, the temperature at the top wall of the microtube increases smoothly from the inlet to the outlet. The graph shows a steady rise in temperature along the tube length, indicating that heat is being transferred from the tube wall to the fluid. The temperature gradient is initially steep but gradually flattens out as the fluid moves towards the outlet. This pattern suggests that the fluid is progressively absorbing heat, leading to an increase in temperature along the tube. The absence of any sharp variations in the graph indicates a uniform heat transfer process without any disturbances, which is typical for fluid flow in a controlled environment with consistent thermal properties.

With the application of a magnetic field of 0.5 Tesla, the temperature distribution along the top wall exhibits noticeable differences. While the overall trend of increasing temperature remains, the graph reveals several inflection points and variations. These fluctuations suggest that the magnetic field is influencing the thermal behavior of the ferro nanofluid, causing localized changes in heat transfer efficiency. The wall temperature at the magnetic field region is about 5% lower as shown in Figure 5. The magnetic field likely alters the alignment and movement of the nanoparticles in the fluid, which affects the fluid's thermal conductivity and heat absorption capacity. As a result, the temperature rise along the tube is less uniform compared to the no-field condition, indicating that the magnetic field introduces complex thermal dynamics into the system.



0.0 Tesla 0.5 Tesla

Figure 5. Static temperature effect on magnetic field at microtube wall.

The effect of temperature at the top wall of a microtube on heat transfer in ferro-nanofluids can be understood through basic heat transfer and fluid dynamics principles. When the wall temperature increases, it creates a steeper temperature gradient between the wall and the fluid. This steeper gradient enhances heat transfer from the wall to the fluid, as per Fourier's law of heat conduction.

As the wall temperature rises, the viscosity of the ferro-nanofluid decreases, making the fluid flow more easily. This lower viscosity allows the fluid to move faster near the heated wall, which improves convective heat transfer by carrying heat away more efficiently. Ferro-nanofluids have unique properties, including higher thermal conductivity, which can increase with temperature. This enhanced thermal conductivity allows the fluid to transfer heat more effectively from the wall into the fluid.

Additionally, higher temperatures cause nanoparticles in the fluid to move more rapidly (increased Brownian motion), which helps distribute thermal energy throughout the fluid. Increased wall temperature can also induce natural convection currents within the fluid due to temperature-induced density differences. These currents further enhance fluid mixing and heat transfer near the wall.

4. Conclusion

The Ansys Fluent simulations on ferro nanofluid flow in a 2D microtube highlight the significant impact of magnetic fields on ferro-nanofluid and thermal properties. When a magnetic field is applied, the temperature distribution along the microtube becomes less uniform, indicating enhanced and spatially variable heat transfer. The pressure profile also becomes more complex, with increased pressure gradients suggesting improved fluid mixing and transport efficiency. These changes demonstrate that magnetic fields can effectively influence the thermal and fluid dynamics within microtube, making them a valuable tool for optimizing thermal management and fluid flow in microfluidic applications.

Additionally, the magnetic field induces fluctuations in fluid velocity, enhancing mixing and altering flow patterns within the microtube. The heat transfer coefficient varies more under the influence of a magnetic field, indicating improved heat transfer efficiency. These findings suggest that magnetic fields can significantly enhance the performance of ferro nanofluids in applications requiring precise heat and fluid management, such as electronics cooling and microfluidic systems. The results show that by applying 0.5 Tesla can increase about 5% in heat transfer coefficient. By controlling the magnetic properties of ferro nanofluids, engineers can develop advanced systems that are both efficient and adaptable to modern technological needs.

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