

An Investigation on the Effect of Magnetic Field on Induced Fluid Flow and Heat Transfer Using CFD-DEM

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ARTICLE INFO	ABSTRACT
<p>Article History: Received: 26 January 2025 Revised: 12 June 2025 Accepted: 02 July 2025 Published: 02 July 2025</p> <p>Article type: Research</p> <p>Keywords: Anisotropic Heat Transfer, CFD-DEM, Convection Heat Transfer, Induced Fluid Flow, Magnetic Nanofluid, Two-Way Coupling</p>	<p>Magnetic nanofluids are innovative materials that have gained significant attention recently due to their unique properties and potential applications in various fields. These fluids consist of magnetic nanoparticles dispersed in a carrier fluid, which can be manipulated by an external magnetic field. A magnetic field causes particles to aggregate in chain-like formations, enhancing their conduction heat flux. This Anisotropic phenomenon has been extensively researched in the literature. This study has also investigated the convection heat flux that arises from the induced fluid flow resulting from particle motion. A numerical simulation was performed using CFD-DEM coupling modeling through COMSOL Multiphysics 6.1. The findings indicate that as the magnetic field strength increases, the chain-like clusters in the magnetic fluid become more prominent, thereby enhancing the anisotropic nature of conduction heat transfer in the fluids. A higher conduction heat flux is observed in magnetic fields parallel to the temperature gradient compared to those perpendicular to it. Furthermore, the motion of the particles disrupted the base fluid's hydrodynamic and thermal boundary layers. No convection heat transfer was detected in magnetic fields of 0.01, 0.02, and 0.05 Tesla. However, at 0.1 Tesla and a 4% volume concentration, a significant disparity was observed between total and conduction heat transfer, suggesting the presence of convection heat transfer.</p>

Introduction

Magnetic nanofluids are nonmagnetic base fluids that contain magnetic nanoparticles, such as iron or its oxides, like magnetite (Fe_3O_4). These particles typically range in size from 1 to 100 nm. To keep the nanoparticles suspended in the system, chemical and physical methods can be used. Examples of these methods include adding surfactants such as oleic acid and using an ultrasonic device [1]. Magnetic nanofluids have the advantage of combining the flowability of the base fluid with the thermal conductivity of solid particles. An external field, such as a magnet, can manipulate magnetic particles, allowing them to act like a smart fluid. In addition to issues concerning heat transfer, magnetic nanofluids have a wide range of uses in various areas, including medicine, biology, electronics, and mechanical engineering. This is due to their adjustable characteristics, making them versatile [2]. Notably, research on the heat transfer

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characteristics of magnetic nanofluids is generally classified into two main categories: conduction and convection.

Many studies have shown that thermal conductivity increases when the magnetic field is aligned with the temperature gradient [3-9]. This creates a chain-like structure along the temperature gradient, facilitating more efficient heat transfer. This characteristic is known as anisotropy due to its dependence on the direction [10]. This phenomenon has also been proved in this research.

Furthermore, the convection heat transfers of magnetic nanofluids were also considered [11]. Volker et al. [12] and Engler et al. [13] conducted experimental studies on natural convection. They found that when a magnetic nanofluid is simultaneously subjected to a magnetic field and a temperature gradient, a net driving force called thermomagnetic convection is created. To better understand thermomagnetic convection, it is essential to consider a specific type of magnetic nanofluid that is temperature-sensitive, with magnetization increasing as the temperature decreases. In such fluids, the magnetization near the cold wall is higher than that near the hot wall. According to Fig. 1, the particles near the wall at temperature T_2 become more magnetized and move more rapidly toward the wall at temperature T_1 ($T_1 > T_2$), following the direction of the external magnetic field (H), which enhances natural convection. Therefore, the Rayleigh number (Ra) is obtained as below [14]:

$$Ra = Ra_T + Ra_m \quad (1)$$

where Ra_T and Ra_m represent thermogravitational Rayleigh number and magnetic Rayleigh number, respectively.

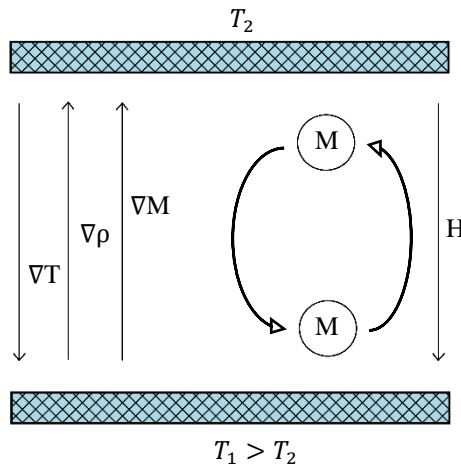


Fig. 1. Schematic representation of the principle behind the situation in which thermomagnetic and natural convection exist

On the other hand, Goharkhah et al. [15] experimentally studied the forced convection of magnetite ferrofluid in a heated tube under the influence of both constant and alternating magnetic fields. The heat transfer enhancement increases significantly by up to 18.9% and 31.4% with the application of a continuous and alternating magnetic field, respectively.

In this study, we do not investigate the effect of temperature on particle magnetization; instead, we focus directly on the influence of particle motion on the base fluid. In addition, to achieve a more precise and accurate analysis of convection heat transfer, we examine the impact of particle motion on fluid velocity disturbances by setting the initial velocity of the base fluid close to zero. These distinctions highlight the differences between this study and prior research on thermomagnetic and forced convection phenomena. A key aspect of this work is to illustrate

how particle movement influences induced fluid flow and ultimately the convection heat transfer. To achieve this goal, a two-way coupling model was implemented using CFD-DEM, where the base fluid and the particles are treated as continuous and discrete phases. The novelty of this research lies in understanding and visualizing the influence of subtle nanoparticle movements on fluid layers and thermal convection.

Modeling

Geometry

A two-dimensional channel with a length of 300 nm has been studied. Two constant temperature boundary conditions are considered at the top and bottom, indicating the hot and cold regions, respectively ($T_h = T_c + 10^{-11} \text{ K}$). To observe the effect of particle movement on the fluid, the fluid velocity should be as low as possible. Therefore, the average inlet velocity is 10^{-20} m/s and is also assumed to be fully developed. The outlet relative pressure is set to zero (Fig. 2).

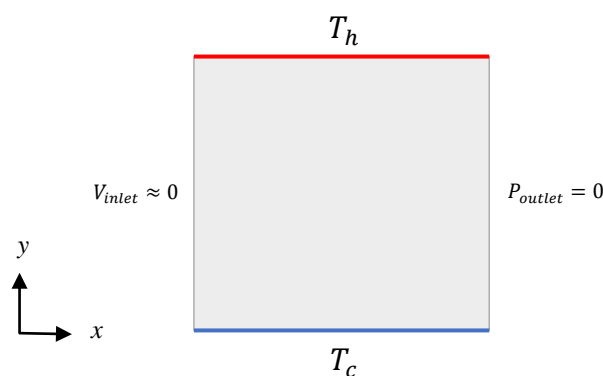


Fig. 2. Geometry and boundary conditions

Once the system has reached a thermally developed condition, 30 nm diameter spherical particles (Fe_3O_4) are randomly dispersed in the base fluid (water). The parameters used for this study are outlined in Table 1. The two-dimensional volume fraction is calculated as the ratio of the area occupied by particles to the total area of the simulation. In this study, the three-dimensional volume fraction was calculated based on the two-dimensional volume fraction using the following relation proposed by Hoomans et al. [16, 17]. This is because the volume fraction calculated in this manner is based on a two-dimensional analysis, which is inconsistent with the empirical correlations used to calculate the drag force acting on a particle that are derived from actual three-dimensional systems. To correct for this inconsistency, the area-based volume fraction (φ_{2D}) was converted to a three-dimensional volume fraction (φ_{3D}) using the following equation.

$$\varphi_{3D} = \frac{2}{\sqrt{\pi\sqrt{3}}} \varphi_{2D}^{3/2} \quad (2)$$

Table 1. Important parameters used in this study

Parameter	symbol	value	Unit
Temperature of the particle and the base fluid	T	293.15	K
Vacuum magnetic permeability	μ_0	$4\pi \times 10^{-7}$	N/A^2
Fluid viscosity	μ	0.000891	$kg/m \cdot s$
Fluid density	ρ_f	0.998	g/cm^3
Particle density	ρ_p	5.15	g/cm^3
Fluid thermal conductivity coefficient	k_f	0.6	$W/m \cdot K$
Particle thermal conductivity coefficient	k_p	3.8	$W/m \cdot K$

Fluid Phase Governing Equations

The base fluid is the continuous phase, and its governing equations are the continuity and Navier-Stokes equations.

$$\frac{\partial(\rho_f \varphi_{3D})}{\partial t} + \nabla \cdot (\rho_f \varphi_{3D} \mathbf{u}) = 0 \quad (3)$$

$$\rho_f \left(\frac{\partial(\varphi_{3D} \mathbf{u})}{\partial t} + (\varphi_{3D} \mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\varphi_{3D} \nabla p + \mu \nabla^2 (\varphi_{3D} \mathbf{u}) + \mathbf{F}^{f-p} \quad (4)$$

where $t, \rho_f, \varphi_{3D}, \mathbf{u}$, are time, fluid density, 3D volume fraction, and fluid velocity vector, respectively. p is fluid pressure, and \mathbf{F}^{f-p} represents volumetric fluid–particle interaction force.

Equations of Particle Motion

Particles are tracked individually and treated as a discrete phase. They have two types of translational and rotational motion defined by linear momentum (Newton's second law of motion) and angular momentum, respectively.

Linear Momentum

Translational motion is the movement of particles with respect to a fixed origin of coordinates. This type of motion is caused by forces acting upon the particles, causing them to move in a specific direction. Therefore, the resultant force determines the position of the particle (\mathbf{r}_i) in the subsequent time step. Where $\mathbf{g}, m_i, \mathbf{v}_i$ are the i th particle's gravity, mass, and linear velocity.

$$\mathbf{F}_i^{Magnetic} + \mathbf{F}_i^{Dipole} + \mathbf{F}_i^{Contact} + \mathbf{F}_i^{Drag} + m_i \mathbf{g} = m_i \frac{d\mathbf{v}_i}{dt} = m_i \frac{d^2 \mathbf{r}_i}{dt^2} \quad (5)$$

External Magnetic Force

In this research, the external magnetic field is uniform, resulting in a zero force. Put another way, the external field does not cause translational motion of particles [18].

$$\mathbf{F}_i^{Magnetic} = \mu_0 (\mathbf{M}_i \cdot \nabla) \mathbf{H} \quad (6)$$

Magnetic Dipole Force

In addition to the external field, each nanoparticle generates a magnetic field that affects its neighbors. \mathbf{F}_{ij}^{Dipole} is the force that the i^{th} -nanoparticle exerts on the j^{th} -nanoparticle. It is directly proportional to the magnetic moment of the particles (\mathbf{M}_i) and inversely proportional to the distance between particles (\mathbf{r}_{ij}).

$$\mathbf{F}_{ij}^{Dipole} = \frac{3\mu_0}{4\pi |\mathbf{r}_{ij}|^5} \left[(\mathbf{M}_i \cdot \mathbf{r}_{ij}) \mathbf{M}_j + (\mathbf{M}_j \cdot \mathbf{r}_{ij}) \mathbf{M}_i + (\mathbf{M}_i \cdot \mathbf{M}_j) \mathbf{r}_{ij} - 5 \frac{(\mathbf{M}_i \cdot \mathbf{r}_{ij})(\mathbf{M}_j \cdot \mathbf{r}_{ij})}{|\mathbf{r}_{ij}|^2} \mathbf{r}_{ij} \right] \quad (7)$$

$$\mathbf{r}_{ij} = \mathbf{r}_j - \mathbf{r}_i \quad (1)$$

The external magnetic field affects the direction and magnitude of the magnetic moment vector (magnetization). It attempts to align the magnetic moment of the particles with itself.

As the field strength increases, the particle magnetization increases and finally reaches a saturation value [19].

Table 2. Magnetization of spherical magnetite particles with a diameter of 30 nm under magnetic fields with different strengths [19]

Magnetic field intensity (T)	0	0.01	0.02	0.05	0.1	0.2	0.5	1
Magnetization (emu/g)	1.2	9	19	34	41	46	52	54

Contact Force

Particles behave like soft spheres, forming an overlap after the collision. The contact force is calculated based on linear spring-dashpot collision concepts proposed by Cundall and Strack [20].

$$\mathbf{F}_{ij}^{Contact} = (K\delta + \gamma(\mathbf{V}_{ij} \cdot \mathbf{e}_{ij})) \mathbf{e}_{ij} \quad (9)$$

$$\mathbf{V}_{ij} = \mathbf{V}_j - \mathbf{V}_i \quad (10)$$

$$\mathbf{e}_{ij} = \frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|} \quad (11)$$

It contains the spring stiffness constant K , the damping term γ , and δ , the overlap value. \mathbf{V}_{ij} , \mathbf{e}_{ij} are the relative velocities of two adjacent particles and the normalized vector of distance between particles.

We can estimate the value of the spring constant and damping term using the following equation, as the ANSYS Fluent guide 2020 R2 suggests:

$$K = \frac{\rho_p d_p \pi |v_{ij}|^2}{3 \varepsilon_D^2} \quad (12)$$

$$\gamma = \frac{-m_p \ln \eta}{t_{collision}} \quad (13)$$

$$t_{collision} = \sqrt{(\pi^2 + \ln^2 \eta) \frac{m_p}{2K}} \quad (14)$$

Where ρ_p , d_p , m_p are particle density, particle diameter, and particle mass. ε_D is the fraction of the diameter for allowable overlap ($\frac{\delta}{d_p}$). η is the coefficient of restitution for the dashpot term and $0 < \eta \leq 1$.

Drag Force

The force applied against the particle from the fluid is called the drag force. The base fluid is a Newtonian fluid, and the flow remains laminar ($Re \ll 1$), so the Stokes equation has been used [21]. \mathbf{U} and \mathbf{V} indicate the fluid and particle velocity vector, respectively.

$$\mathbf{F}_i^{Drag} = \frac{18\mu}{\rho_p d_p^2} m_p (\mathbf{U} - \mathbf{V}) \quad (2)$$

Angular Momentum

Rotational motion is the movement of particles relative to their center, which is caused by the torque acting on them. Therefore, the resultant torque determines the angular position of the particle (θ_i) in the next time step [22].

$$\mathbf{T}_i^{Field} - \xi_r \boldsymbol{\omega}_i = I_i \frac{d\boldsymbol{\omega}_i}{dt} = I_i \frac{d^2 \theta_i}{dt^2} \quad (3)$$

Where T_i^{Field} , ξ_r , ω_i , I_i are the external magnetic moment, rotational drag force coefficient, angular velocity, and moment of inertia, respectively.

$$T_i^{Field} = \mathbf{M}_i \times \mathbf{H} \quad (4)$$

$$\xi_r = \pi d_p^3 \mu \quad (5)$$

$$I_i = m_i \frac{d_p^2}{10} \quad (6)$$

Thermal Equation

The equation of heat transfer in Cartesian coordinates containing fluid is as follows [21].

$$\rho_f C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) + \nabla \cdot (-k_{cell} \nabla T) = 0 \quad (7)$$

Where C_p , T , k_{cell} are the specific heat capacity at constant pressure, absolute temperature, and the thermal conductivity coefficient of the cell. The thermal conductivity coefficient of a cell is determined by the material occupying it. The values of 0.6 and 3.8 W/m.K are regarded as the respective properties of fluid and particle. By default, in COMSOL Multiphysics 6.1, k_{cell} equals k_f (0.6 W/m.K). Thus, for regions containing particles, a UDF code was written to correct k_{cell} to reach k_p (3.8 W/m.K). For areas containing both particles and fluid, the thermal conductivity is determined by averaging the values of the particles and the fluid.

Simulation Details

Heat Transfer Coefficient

As seen in Fig. 2, the temperature gradient is aligned with the y-axis. Therefore, the heat flux is computed in this direction, which includes both conduction and convection.

$$q_{total|y} = q_{conduction|y} + q_{convection|y} \quad (8)$$

$$k_{eff} = \frac{q_{total|y}}{\partial T / \partial y} = \frac{q_{conduction|y}}{\partial T / \partial y} + \frac{q_{convection|y}}{\partial T / \partial y} = k + f(h) \quad (9)$$

Where k is the thermal conductivity of the system, and $f(h)$ indicates the convective heat transfer coefficient, computed using Fourier's law. k is attributed to particle chaining and has been extensively studied in the literature, but $f(h)$ is a novel concept and arises from induced fluid flow. To compute k , a one-way coupling modeling approach was employed to avoid any induced fluid flow. In contrast, $f(h)$ requires a two-way coupling modeling approach with a constant thermal conductivity coefficient of 0.6 W/m.K for the cell to avoid any chain-like effects. Ultimately, $f(h)$ is obtained by deducting the thermal conductivity contribution of water from the heat flux.

Cut-off Radius

F_{ij}^{Dipole} is influenced by the presence of other particles. However, as the strength of this force diminishes significantly with increasing distance ($F_{ij}^{Dipole} \sim \frac{1}{|r_{ij}|^5}$), it is possible to limit its application within a specific range to reduce computation time. This range is defined as the cut-off radius, which is set at 2.5 times the diameter of the particles [23]. Beyond this radius,

the magnetic dipole force between particles is considered zero (as shown in Fig. 3). The UDF code is executed from 70 microseconds onwards.

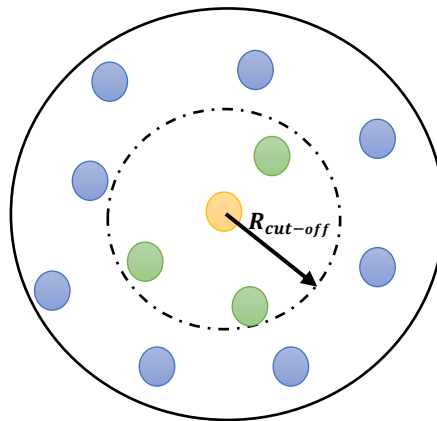


Fig. 3. The cut-off radius of a magnetic particle [23]

Results and Discussion

The results of this study are presented in three aspects, organized as follows. The trajectory of magnetic particles, along with a discussion of macro- and micro-scale phenomena in the chaining process, is presented first. This is followed by a debate on the induced flow during the chaining process. This section ends with a detailed discussion about the thermal effect of induced flow during the chaining of magnetic nanoparticles.

Particle Motion and Chaining Process

A simulation was conducted to investigate the chaining of nanoparticles under the conditions described in the modeling section. The snapshots of the nanoparticles' position, velocity, and magnetic moment vector (Arrow) are illustrated in Fig. 4. The spheres and arrows are colored according to the magnitude of translational and angular velocity, which is attributed to the dipole force (Eq. 7) and external torque (Eq. 17), respectively. Nanoparticles are dispersed randomly inside the domain at zero time. As can be seen in this Figure, the dispersed nanoparticles in a fluid condition are gradually transformed into chained ones over time. At the early stage of this process (i.e., $t = 0.1 \mu\text{s}$), the nanoparticles move and rotate due to dipole and external magnetic forces. The translational and angular velocities of nanoparticles are low, and the arrows of angular velocity are in various directions. After elapsing $1 \mu\text{s}$ of the process, when the particles move towards each other, and the distance between the nanoparticles is reduced, the translational velocity increases. However, the contact force (Eq. 9) prevents two particles from overlapping completely. The angular velocity increases until the particles align with the external magnetic field ($2 \mu\text{s}$). Consequently, when particles reach each other, the translational velocity of the particles decreases considerably, and they form chain-like structures. In this situation, the contact force compensates the dipole force. By creating these primer chains, the movement of particles within the chain becomes more restricted, and in return, the chain-like structures grow. Finally, at $100 \mu\text{s}$, no motion of particles is observed, suggesting that the magnetic nanofluid had achieved stability. Nanoparticles are shaped in a chain along the y-axis due to the influence of the magnetic field, resulting in anisotropic properties.

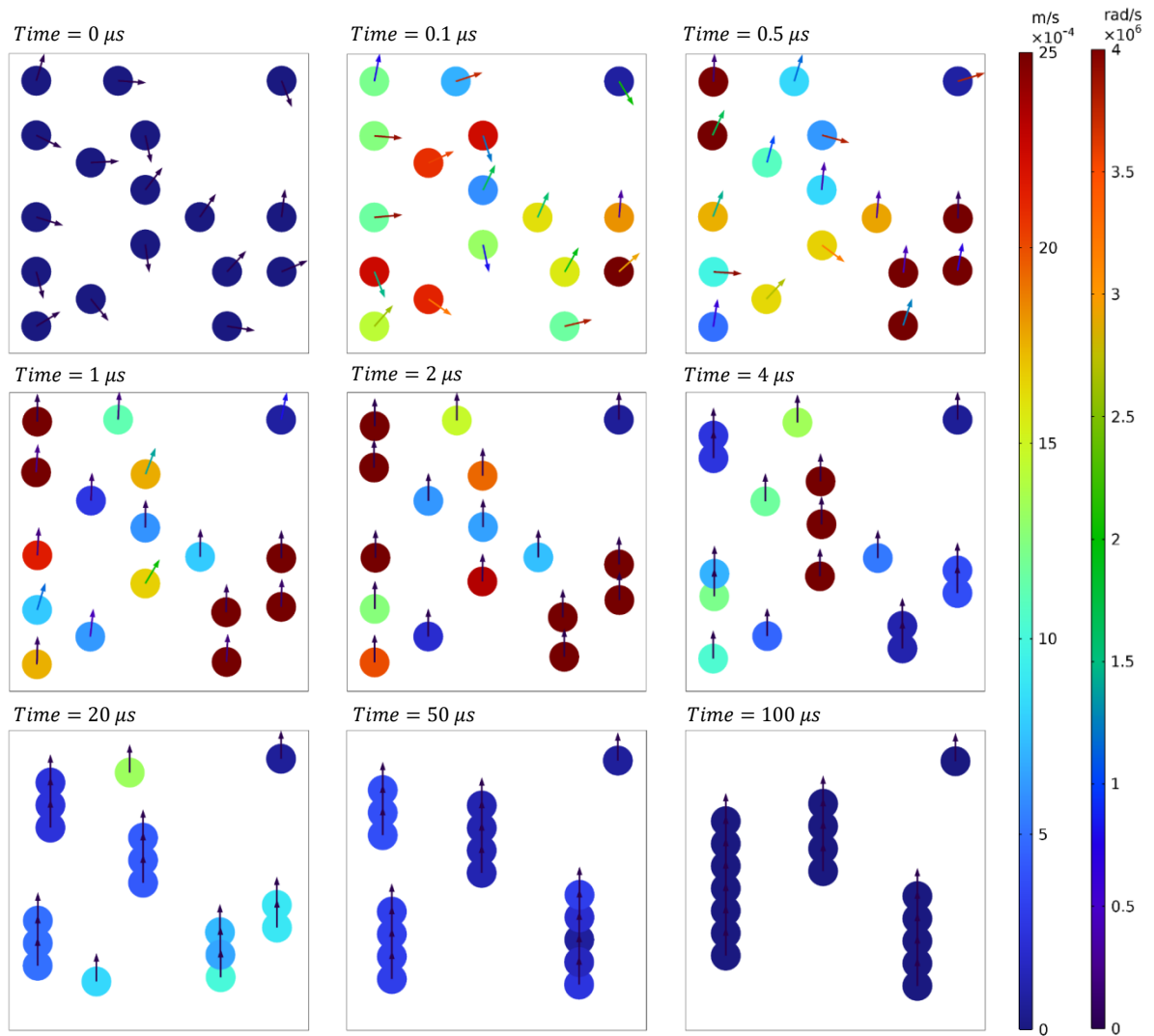


Fig. 4. Position, translational velocity (m/s), and angular velocity (rad/s) of the particles in a magnetic nanofluid containing 4% volume fraction nanoparticle under a magnetic field of 0.1 Tesla over time

Induced Fluid Flow

The movement of particles in the domain leads to fluid flow and disturbance in the hydrodynamic boundary layer. As the induced fluid velocity can vary significantly, the results are divided into three stages: initial, intermediate, and final.

Initial Time

Fig. 5 illustrates the induced fluid velocity at the initial times in picoseconds. The legend values are based on the input velocity of the base fluid. It is evident that after one ps, the fluid is disturbed, which is much more sensitive than the particle, requiring a smaller time step. At 10 ps, the picture turns almost red, indicating that a legend with a more significant order should be used.

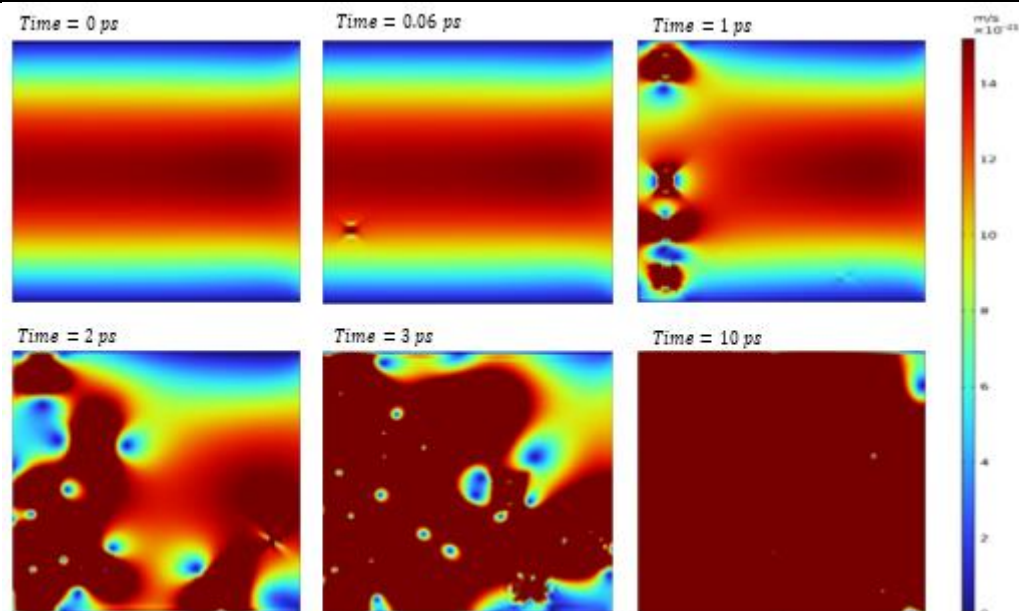


Fig. 5. Induced fluid velocity at initial time in a magnetic nanofluid containing 4% volume fraction nanoparticle under a magnetic field of 0.1 Tesla over time

Intermediate Time

Fig. 6 illustrates the induced fluid velocity at intermediate times in microseconds, with a legend in units of 10^{-11} m/s. For a better description of the process, snapshots of the spatial velocity distribution of particles in the same bed as described in Fig. 4 are shown in Fig. 6. An increase in particle speed corresponds to a rise in fluid velocity. This phenomenon is displayed in moments of 1 and 2 microseconds. As can be seen in this Figure, the induced flows gradually disappear as the translational and rotational movement of particles and chain-like structure formation decrease.

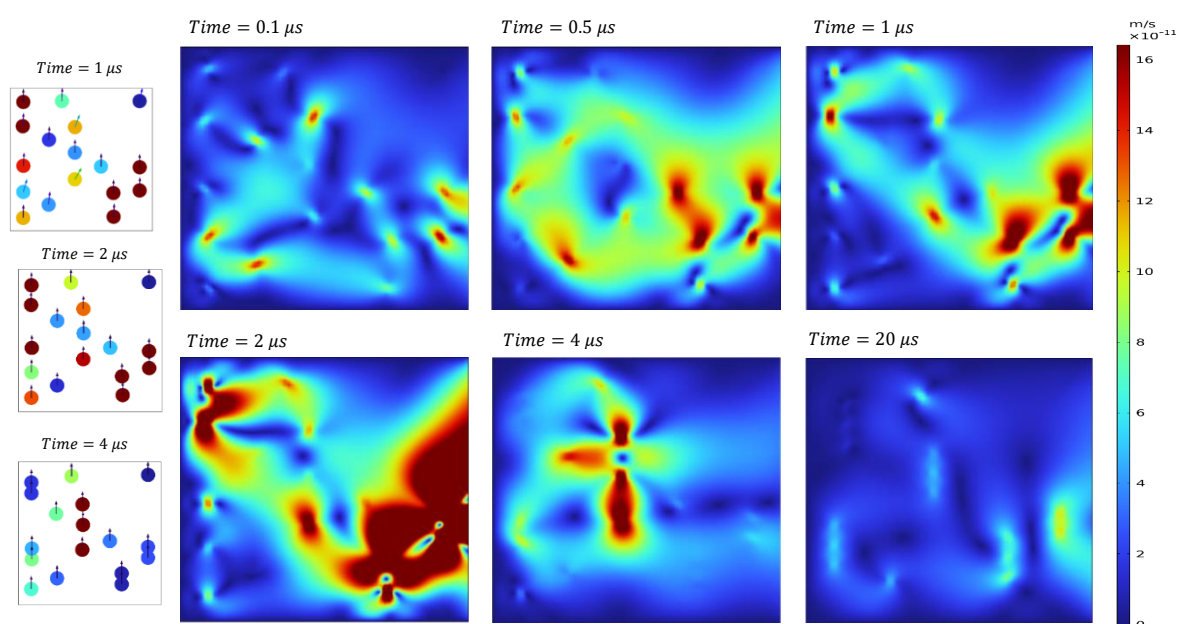


Fig. 6. Induced fluid velocity at intermediate time in a magnetic nanofluid containing 4% volume fraction nanoparticle under a magnetic field of 0.1 Tesla over time

Final Time

The induced fluid velocity decreases during the stability of the magnetic nanofluid. As the distance between particles or chains increases (beyond 100 microseconds), the dipole force decreases, and they no longer affect one another. Meanwhile, the external magnetic field is constant and doesn't cause any translational motion. This combination of factors stabilizes the magnetic nanofluid and returns to its initial velocity boundary layer state (Fig. 7).

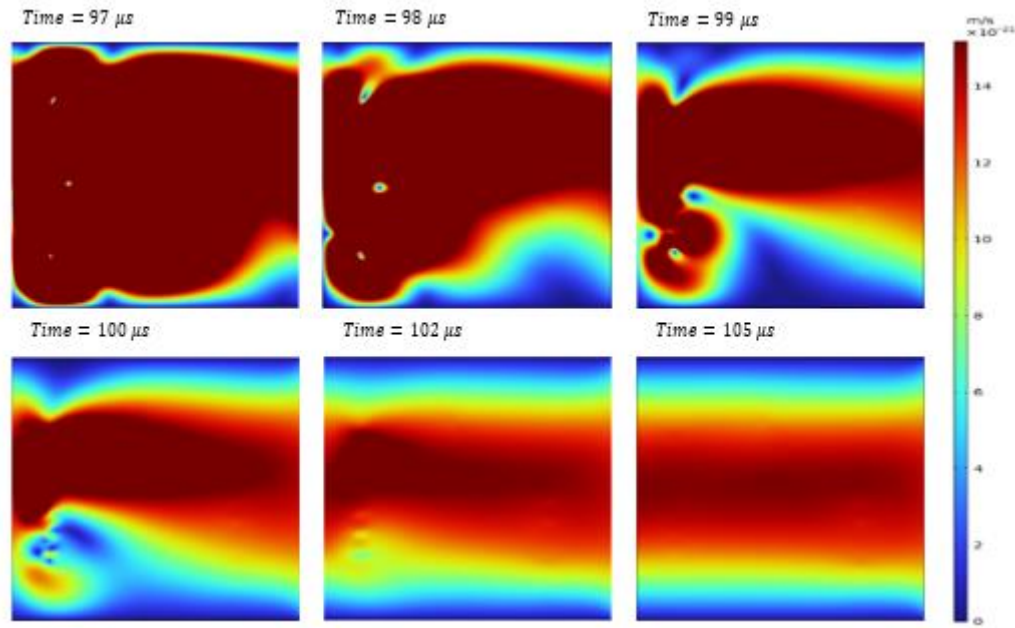


Fig. 7. Induced fluid velocity at final time in a magnetic nanofluid containing 4% volume fraction nanoparticle under a magnetic field of 0.1 Tesla over time

Thermal Behavior of Magnetic Nanofluid

Temperature Gradient

The particles in a fluid can cause disturbances in the thermal boundary layer due to their differing thermal conductivities and the induced fluid flow. This phenomenon is illustrated in Fig. 8, which depicts the dimensionless temperature contour of the base fluid with and without particles. In the absence of particles, the temperature distribution is determined by the distance from the hot and cold walls. However, the layer is disrupted in the presence of particles, leading to an altered boundary layer structure. Nanoparticles have higher thermal conductivity than the base fluid (3.8 to 0.6 w/m.K), and a magnetic field enables them to enhance heat transfer by bridging hot and cold zones. The dimensionless temperature of the fluid is defined as follows.

$$\theta = \frac{T - T_c}{T_H - T_c} \quad (10)$$

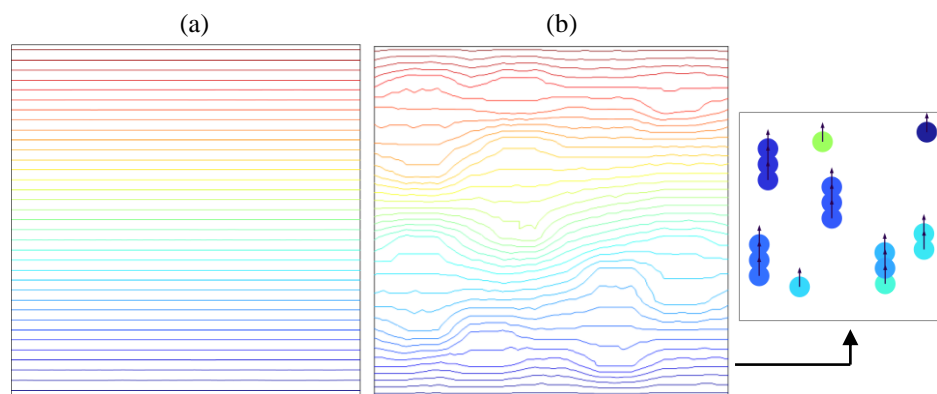


Fig. 8. Dimensionless temperature contour of the base fluid (a) without and (b) with particles in a magnetic nanofluid containing 4% volume fraction of nanoparticles under a magnetic field of 0.1 Tesla at $t = 20 \mu s$

Conduction Heat Transfer (k)

Thermal Conductivity in the Absence of a Magnetic Field

Fig. 9 illustrates the ratio of the magnetic nanofluid thermal conductivity coefficient (k) to the base fluid (k_f) at various concentrations without a magnetic field. The diagram presents results from experimental research conducted by Zhu et al. [24] and Abareshi et al. [25], as well as computational modeling performed in this study and classical models such as Maxwell and Jeffrey models. According to Fig. 9, classical models are not suitable for predicting the thermal conductivity of nanoparticles. The diameter of the particles in Zhu et al.'s experiment was 10 nm, while the present work used 30 nm particles. In the study by Abareshi et al. [25], cubic-shaped nanoparticles with sizes ranging from 15 to 22 nanometers were used. These variations in particle size and shape contributed to the differences observed in the values presented in the graph. Overall, increasing the concentration leads to an increase in the thermal conductivity coefficient in the nanofluid.

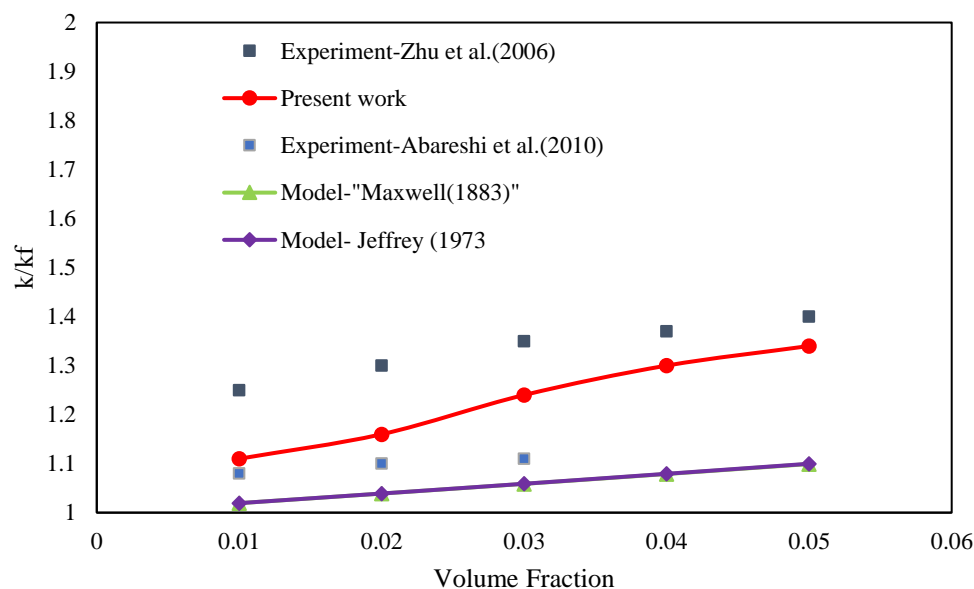


Fig. 9. The ratio of thermal conductivity coefficient of magnetic nanofluid to base fluid (water) at various concentrations without a magnetic field

Thermal Conductivity under a Parallel Magnetic Field

Fig. 10 illustrates how the system's thermal conductivity coefficient relative to the base fluid (k/k_f) increases over time. The increase is evident in chain formation, particularly at higher volume fractions. Anisotropic properties formed by magnetic nanoparticles act as solid bridges. This phenomenon has been observed many times in the literature [4, 5, 26, 27].

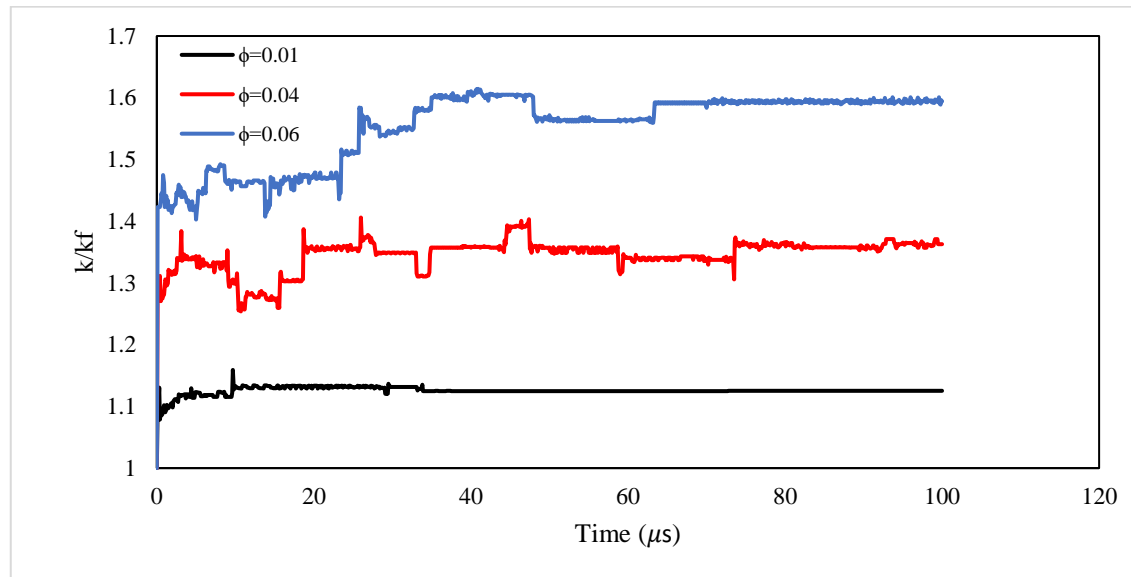


Fig. 10. The ratio of thermal conductivity coefficient of magnetic nanofluid to base fluid (water) at 0.1 T in the presence of a parallel magnetic field

Thermal Conductivity under a Perpendicular Magnetic Field

Fig. 11 illustrates the thermal conductivity under a 1 Tesla magnetic field in both parallel and perpendicular directions to the temperature gradient. The concentration increase enhances thermal conductivity in both directions, with a more pronounced effect when the magnetic field is aligned. The anisotropic structure resulting from chain formation, as shown in Fig. 4, suggests anticipated variations in thermal behavior based on alignment with or perpendicular to the magnetic field direction.

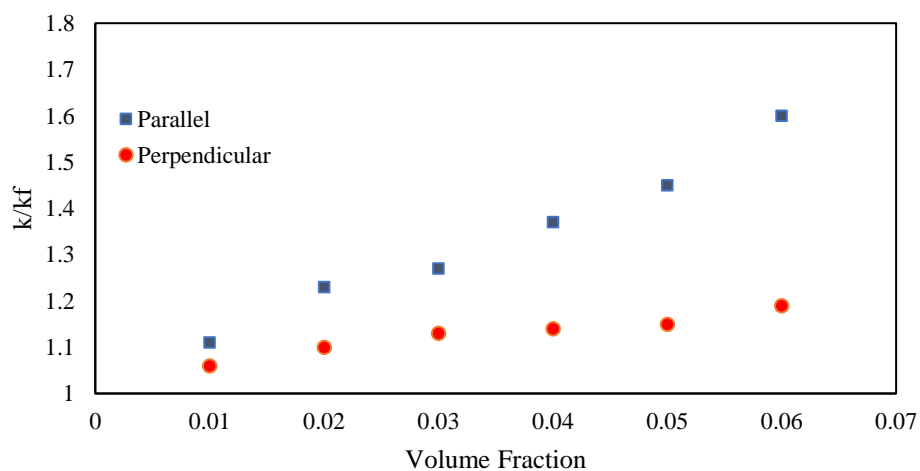


Fig. 11. The thermal conductivity ratio in magnetic nanofluid to water under a 1 Tesla magnetic field at different volume fractions in both parallel and perpendicular magnetic fields

Convection Heat Transfer ($f(h)$)

In the absence of a magnetic field and even magnetic fields of 0.01, 0.02, and 0.05 Tesla, no remarkable convection heat transfer was observed (Fig. 12). It means the induced fluid flow in these intensities cannot increase the convection coefficient and therefore $f(h) \approx 0$ (Eq.22).

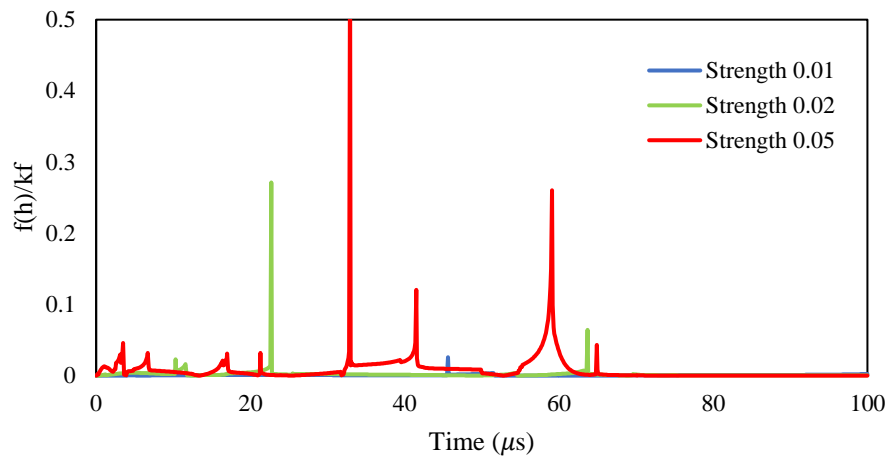


Fig. 12. The ratio of convection heat transfer coefficient in a magnetic nanofluid containing 4% volume fraction nanoparticle under a magnetic field of 0.01, 0.02, and 0.05 Tesla to the base fluid thermal conductivity coefficient over time

Fig. 13 shows convection heat transfer coefficient changes for a 4% volume fraction magnetic nanofluid under a 0.1 Tesla field, compared to the base fluid thermal conductivity coefficient ($f(h)/k_f$) over time. Particle movement causes induced fluid flow, leading to enhanced convection heat transfer. It demonstrates up to a 40% enhancement in thermal convection compared to pure water. In contrast, Ashjaee et al. [28] reported a 38% increase in convective heat transfer for a 3% volume fraction under a 0.12 Tesla magnetic field in laminar flow conditions. However, beyond 50 microseconds, chain movement lacks the speed needed to sustain induced fluid flow and further increase convection heat transfer.

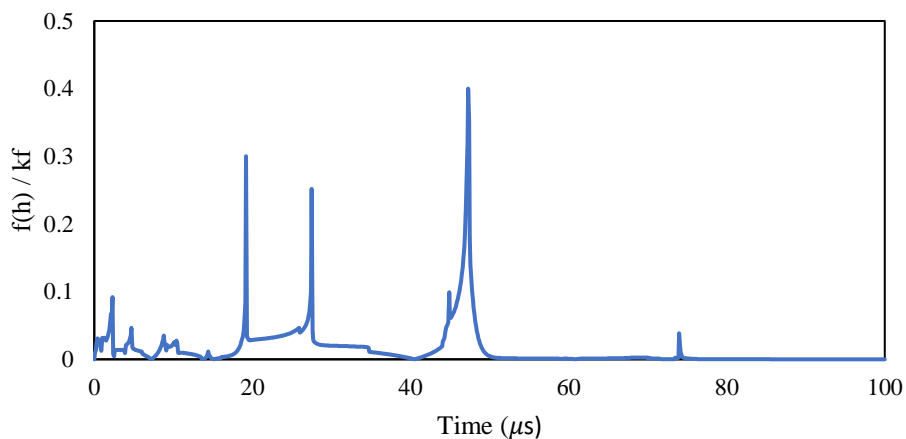


Fig. 13. The ratio of convection heat transfer coefficient in a magnetic nanofluid containing 4% volume fraction nanoparticle under a magnetic field of 0.1 Tesla to the base fluid thermal conductivity coefficient over time

Total Heat Transfer Coefficient ($k_{eff} = k + f(h)$)

As seen in Fig. 14, a gap exists between the k_{eff} and k graphs due to the presence of $f(h)$. This distinction is noticeable before the magnetic nanofluid achieves a stable state. However, starting at 50 microseconds, these two graphs coincide. As shown in Fig. 4, the formation of

long particle chains indicates that the particles have nearly reached a stable state within the nanofluid and can no longer move freely, thereby contributing to thermal convection.

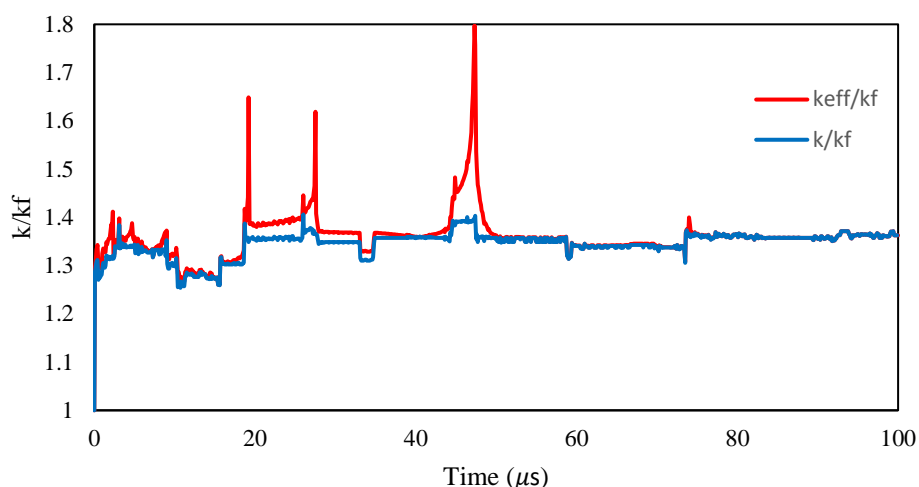


Fig. 14. Comparison of the total heat transfer coefficient (k_{eff}/k_f) and thermal conductivity (k/k_f) of a magnetic nanofluid under a 0.1 Tesla field at a 4% volume fraction

Conclusion

The CFD-DEM method was used to investigate the induced fluid flow and thermal behavior of the magnetic nanofluid. Our findings can be summarized as follows:

- With an external magnetic field, particles exhibit translational and rotational motion, disrupting the fluid velocity profile. The fluid velocity is directly proportional to the particle velocity.
- Upon achieving stability in the magnetic nanofluid, the hydrodynamic boundary layer reverts to its initial state.
- The particle's thermal conductivity and induced fluid flow disrupt the fluid temperature profile.
- The model presented demonstrated superior prediction of thermal conductivity enhancement compared to the classical Maxwell and Jeffrey models in the absence of the magnetic field.
- Chaining of particles causes anisotropic properties and ultimately improves thermal conductivity along the temperature gradient.
- In magnetic fields with intensities of 0.01, 0.02, and 0.05 Tesla, the induced fluid flow is insufficient to enhance convective heat transfer. However, at a magnetic field strength of 0.1 Tesla, a considerable gap is observed between thermal conductivity and total heat transfer, indicating the presence of convection heat transfer.

Nomenclature

T_h	hot wall of the channel (K)	T_c	cold wall of the channel (K)
φ	volume fraction (-)	ρ	density (kg/m^3)
μ	fluid viscosity ($kg/m \cdot s$)	Re	Reynolds number
\mathbf{u}	fluid velocity (m/s)	\mathbf{V}	particle velocity (m/s)
μ_0	vacuum magnetic permeability (N/A^2)	\mathbf{g}	acceleration of gravity (m/s^2)
\mathbf{M}_i	magnetic moment of particle i ($A \cdot m^2$)	\mathbf{r}_i	position of particle i (m)
\mathbf{e}_{ij}	unit vector position of particle i	\mathbf{F}_i	force on particle i (N)
$\mathbf{F}_i^{\text{Drag}}$	drag force on particle i (N)	$\mathbf{F}_{ij}^{\text{Dipole}}$	magnetic force on particle i from particle j (N)
$\mathbf{F}_i^{\text{Magnetic}}$	external magnetic force on particle i (N)	$\mathbf{F}_{ij}^{\text{Contact}}$	contact force on particle i from particle j (N)
\mathbf{H}	magnetic field (T)	K	spring constant (N/m)
γ	damping term (N.s/m)	δ	overlap value (m)
I_i	moment of inertia of particle i ($kg \cdot m^2$)	\mathbf{q}	heat flux (W/m^2)
ω_i	angular velocity of particle i (rad/s)	k_{eff}	effective heat transfer coefficient ($W/m \cdot K$)
θ_i	angular position of particle i (rad)	k	conduction heat transfer coefficient ($W/m \cdot K$)
ξ_r	rotational drag coefficient of particle i ($kg \cdot m^2/s$)	$f(h)$	convection heat transfer coefficient ($W/m \cdot K$)
m_i	mass of particle i (kg)	$R_{cut-off}$	cut-off radius (m)
d_p	particle diameter (m)	t	time (s)
$\mathbf{T}_i^{\text{field}}$	torque of external magnetic field on particle i (N.m)		

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