Hydro-thermal interactions of a ferrofluid in a non-uniform magnetic field

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Abstract
A numerical study is performed to examine the influence of a non-uniform magnetic field on the thermo-hydraulic behaviour of a ferrofluid. The analysis is done in the context of a differentially heated semi-circular annulus where a magnetic dipole with its distinct location and dipole strength is used to obtain different configurations. The field variables are computed by solving the coupled set of flow equations, energy equations and the Maxwell’s magneto-statics equations. A detailed description is provided on the flow and thermal response after observing different parameters at both global and local scale. Comparison of streamlines and isotherms with a reference case of natural convection concludes that the recirculation zones are responsible for the increased velocity and heat transfer magnitudes. Another key finding of the present work is about the possibility to locally improve the thermal performance of heat exchangers at any desired position along the circumference.

Nomenclature

\( a \) Abscissa of dipole [m]
\( b \) Ordinate of dipole [m]
ACW Anti-ClockWise
\( B, \vec{B} \) Magnetic flux density [Wb/m²]
CW ClockWise
\( g \) Acceleration due to gravity [m/s²]
\( H, \vec{H} \) Magnetic field strength [A/m]
\( k \) Thermal conductivity [W/m.K]
\( K_B \) Boltzmann constant [J/K]
KFD Kelvin Force Density
\( L \) Length [m]
\( m \) Magnetic moment [A.m²]
\( M, \vec{M} \) Magnetization [A/m]
\( M_d \) Bulk magnetization [A/m]
\( M_n \) Magnetic number [-]
\( Nu \) Nusselt number [-]
\( p \) Pressure [Pa]
\( R \) Radius [m]
\( Ra \) Rayleigh number [-]
\( Re \) Reynolds number [-]
\( t \) Time [s]
\( T \) Temperature [K]
TMC Thermo-Magnetic Convection

Greek Symbols

\( \alpha \) Thermal diffusivity [m²/s]
\( \beta \) Coefficient of volumetric expansion [1/K]
\( \mu \) Dynamic viscosity [Pa.s]
\( \mu_o \) Permeability of free space [kg.m/s².A²]
\( \nu \) Kinematic viscosity [m²/s]
\( \phi \) Volume fraction [-]
\( \Phi_H \) Magnetic scalar potential [A]
\( \rho \) Density [kg/m³]
\( \xi \) Ration of magnetic energy to thermal energy [-]

Subscripts

\( A_\infty \) Ambient
\( A_{avg} \) Average magnitude
\( A_C \) Cold
\( A_f \) Fluid
\( A_H \) Hot
\( A_i \) Inner
\( A_{local} \) Local magnitude
\( A_{nf} \) Nanofluid mixture
\( A_o \) Outer
\( A_s \) Solid

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1 Introduction

Because of their distinct thermo-physical and magnetic properties [1–3], ferrofluids are being widely used to regulate as well as to enhance the heat and flow characteristics [4–6]. Various studies have been performed by researchers to investigate the mechanism of Thermo-Magnetic Convection (TMC) using a non-uniform magnetic field obtained from different sources such as magnetic dipole [7–10], electric wire [11–13], permanent magnet, [14–17], and solenoid [18–20]. TMC occurs in magnetic fluids that exhibit temperature dependent magnetic susceptibility. These fluids when exposed to an external magnetic field along with a thermal gradient, experience the presence of varying volumetric forces. Such unbalanced body forces eventually results in the movement of cold magnetic fluid to the region of higher magnetic field strength and vice-versa.

One of the foremost works that employs the use of magnetic fluid to control the flow and heat transfer in a concentric annulus is performed by Sawada et al. [21]. After several experimental observations, authors concluded that irrespective of its magnitude, an external magnetic field has considerable influence on the heat transfer mechanism. Singh et al. [22] later studied a similar configuration that implements a radial magnetic field to manipulate a fully developed laminar convection inside a vertical annulus. They provided exact solutions for the temperature and velocity field within the annulus, along with skin friction coefficient and mass flow rate. A numerical and an experimental investigation is carried out by Wrobel et al. [12] to understand TMC of a paramagnetic fluid inside the annulus of two vertical co-axial cylinders. After comparing the Nusselt number (\( Nu \)) among various orientations, authors suggested the use of a strong magnetic field for an enhanced thermal performance. In addition to the circular annulus, TMC is also explored by many researchers in several other geometrical domains, such as rectangular duct [10, 23, 24], helical duct [25], concentric pipes [26, 27], cylinder [28, 29], and square cavity [7, 17, 30–32]. In general, all of the aforementioned studies concluded that a non-uniform magnetic field alters the velocity profile within the magnetic fluid, which ultimately influences the thermal as well as the flow distribution inside the ferrofluids.

In the past, several researchers have employed a magnetic dipole to obtain the non-uniform magnetic field distribution which is an essential requirement for TMC. Ganguly et al. [7] studied the influence of a dipole on a differentially heated square enclosure filled with magnetic fluid and demonstrated that TMC can be implemented effectively for the micro-scale energy transfer. The same configuration is further analysed by Mukhopadhyay et al. [9] and authors proposed a correlation to predict the \( Nu \) in terms of the magnetic Rayleigh number. Ganguly et al. [8] also investigated the influence of magnetic dipoles on forced ferrofluid convection in a 2D channel at a fixed \( Re = 11.8 \). Further, an identical domain is simulated by Strek and Jopek [33] but with a parabolic inlet velocity profile and authors concluded that there exists a threshold value of \( H \) that is required to overcome the viscous forces. Numerical work on the same problem statement is further extended by Goharkhah and Ashjee [34] to understand the effect of different \( Re \) and frequency used to control the magnetic dipoles. In addition to the aforementioned studies, other numerical investigations [10, 35] have also been conducted to explore the effect of varying \( H, Re \), location and number of magnetic dipoles on two dimensional ferrofluid channel flow.

As mentioned earlier, several studies have been carried out in the past to understand the TMC mechanism inside different geometrical domains using various sources of magnetic field. However, relatively little literature is available that discusses the hydro-thermal interactions of TMC within annular cross-sections. This specific shape is of prominent importance as it is being widely used in heat exchanger applications [36, 37]. Thus, the objective of the present work is to improve our understanding about the ferrofluid based TMC within a semi-circular annulus. To accomplish that, 9 different TMC configurations (three distinct dipole locations and three different dipole strengths \( \mu Mn = 6.433 \times 10^{10}, Mn = 2.573 \times 10^{11}, and Mn = 1.029 \times 10^{12} \) are closely observed in the present numerical work for their distinct flow and thermal behaviour at a fixed \( Ra \) of \( 10^6 \).

2 Problem description

For the present analysis, a 2-D semi-circular annulus of a fixed \( L/D \) ratio \( (L = 0.8) \) is considered as shown in Fig. 1, where \( L \) is the width of annulus \( (L = R_o - R_i) \) and \( D \) represents the internal diameter \( (D = 2R_i) \). Such annular shapes generally exhibit the physical symmetry, and hence only half of the domain is investigated in the current work to reduce the computational requirements. The inner wall of the annulus is maintained at relatively higher temperature \( (T_H) \) (compared to its outer wall \( (T_c) \)) and the working domain is considered to be completely filled with a water based colloidal suspension of Fe3O4 nanoparticles. These nanoparticles contribute to the varying magnetic behaviour of the working fluid in accordance with their corresponding volume fraction (\( \phi \)). To observe the TMC within this enclosure, a non-uniform magnetic field is obtained with the help of a magnetic dipole that is placed at
3 Numerical methodology

3.1 Governing equations and boundary conditions

In the present work, all three magnetic field variables \( B, H, \) and \( M \) are considered with the help of Maxwell’s equations of magneto-statics as shown in Eq. 4.

Maxwell’s Equations

\[
\nabla \cdot B = 0, \quad \nabla \times H = 0, \quad \text{and} \quad B = \mu_0(H + M)
\]

(4)

Here, \( B \) refers to the magnetic flux density, \( H \) is the magnetic field, and both are coupled via magnetic permeability \((\mu_0 = 4\pi \times 10^{-7} \text{ kg.m/s}^2.\text{A}^2)\) and magnetization \((M)\). To approximate this magnetization of the ferrofluid mixture, a superparamagnetic law [1] is implemented that takes into account the effect of varying \( T, H \) and \( \phi \) as shown in Eq. 5:

\[
M = M_d\phi \left[ \coth(\alpha) - \frac{1}{\alpha} \right] \quad \text{where} \quad \alpha = \frac{\mu_0mH}{K_B T}
\]

(5)

In the above equation, \( M_d \) (446 kA/m) represents the bulk magnetization of solid \( \text{Fe}_3\text{O}_4 \) particles and \( K_B \) (1.3 \times 10^{-23} \text{ kg.m/s}^2.\text{K}) is the Boltzmann constant. In addition to the magnetic field variables, flow field variables \((p, U, T)\) for an incompressible, non - isothermal, and electrically non - conducting ferrofluid are determined with the help of Eqs. 6–8:

Continuity Equation

\[
\nabla \cdot U = 0
\]

(6)

Momentum Equation

\[
\rho_nf \left[ \frac{\partial U}{\partial t} + (U \cdot \nabla)U \right] = -\nabla p + \rho_nf \nabla^2 U + \mu_0(M \cdot \nabla)H + g(\rho_{nf} - \rho_{\infty})
\]

(7)

Energy Equation

\[
(\rho C_{p})_{nf} \left[ \frac{\partial T}{\partial t} + (U \cdot \nabla)T \right] = k_{nf} \nabla^2 T
\]

(8)

In Eqs. 6–8, \( U, t, p, \) and \( T \) represent velocity, time, pressure and temperature of the entire mixture, respectively. In Eq. 7, \( \mu_0(M \cdot \nabla)H \) represents a volumetric body force experienced by the \( \text{Fe}_3\text{O}_4 \) mixture due to the presence of a non-uniform magnetic field. This term is often referred as the Kelvin Force Density (KFD) which results in the motion of the working fluid towards the region of higher magnetic field. Additionally, \( g(\rho_{nf} - \rho_{\infty}) \) refers to the Boussinesq approximation that takes into account the movement of ferrofluid solely due to the density difference. Moreover, \( \rho_{nf} \) and \((C_p)_{nf}\) is the density and the specific heat of the mixture that is calculated using the corresponding contribution of particles \((\phi = 0.05)\) in the mixture:

Fig. 1 Geometrical representation of the present case

a radial distance of 0.75\( R_i \) from the centre in three different orientations \((\theta = 60^\circ \text { for location A, } \theta = 0^\circ \text { for location B, and } \theta = -60^\circ \text { for location C})\) as shown in Fig. 1.

The non-uniform magnetic field distribution of each magnetic dipole is computed using the magnetic scalar potential \( (\Phi_H) \) [38] as shown in Eqs. 1–3. The individual components \((H_x, H_y)\) are defined as a function of their Cartesian coordinates for any specific \( \gamma \) that is derived from the corresponding \( H \). Further, to have a better comparative evaluation, the non-dimensionalised distribution of the strength of magnetic field \((H^* = H/\widehat{H})\) where \( H = \sqrt{H_x^2 + H_y^2} \) and \( \widehat{H} = \gamma /2\pi b \) is shown in Fig. 3 for all three locations.

\[
\Phi_H(x, y) = \frac{\gamma}{2\pi} \left[ \frac{(x - a)}{(x - a)^2 + (y - b)^2} \right]
\]

(1)

\[
H_x = -\frac{\partial \Phi_H}{\partial x} = \frac{\gamma}{2\pi} \left[ \frac{(x - a)^2 - (y - b)^2}{[(x - a)^2 + (y - b)^2]^2} \right]
\]

(2)

\[
H_y = -\frac{\partial \Phi_H}{\partial y} = \frac{\gamma}{2\pi} \left[ \frac{2(x - a)(y - b)}{[(x - a)^2 + (y - b)^2]^2} \right]
\]

(3)
Here, the subscript \( f \) and \( s \) refer to the fluid component and solid component whose corresponding properties are mentioned in Table 1. To compute the viscosity of the \( \text{Fe}_3\text{O}_4 \) mixture (\( \mu_{nf} \)), a \( \phi \) dependent correlation is used as mentioned in Eq. 10. Further, to calculate thermal conductivity (\( k_{nf} \)), the Hamilton - Crosser model [39] is implemented as shown in Eq. 11 where \( n = 3 \) for spherical particles.

\[
\mu_{nf} = \mu_f \left( 1 + \frac{5}{2} \phi + \frac{25}{4} \phi^2 \right) \quad (10)
\]

\[
k_{nf} = k_f \left[ \frac{k_s + (n - 1)k_f}{k_s + (n - 1)k_f + (k_f - k_s)\phi} \right] \quad (11)
\]

The afore-stated group of governing equations is closed by using the boundary conditions for the respective field variables (as defined in Table 2) along with the dimensionless parameters mentioned below

\[
Ra = \frac{g\beta(T_H - T_C)l^3}{\nu_{nf}a_{nf}}, \quad \text{and} \quad Mn = \frac{\mu_0\tilde{H}^2l^2}{\rho_{nf}a_{nf}^2} \quad \text{where} \quad \tilde{H} = \frac{\gamma}{2\pi b} \quad (12)
\]

### 3.2 Grid independence study and model validation

The semi-circular domain is discretized into a structured non-uniform grid that entirely consists of quadrilateral elements as shown in Fig. 2. To capture the large field gradients, fine spacing is also provided near both the walls with a gradual expansion ratio. Moreover, to ensure that the present numerical work is free of discretization errors, five different grid configurations are compared for their results. The comparison is carried out for a specific case of TMC corresponding to \( Ra = 10^6 \), \( Mn = 2.573 \times 10^{11} \), and location B (refer sub-figure 3b). The domain averaged values of...
velocity \((U_{avg})\) and temperature \((T_{avg})\) are computed for all the grids using the equation shown below

\[
\begin{align*}
T_{avg} &= \frac{1}{S} \int_{0}^{S} T \, dS \\
U_{avg} &= \frac{1}{S} \int_{0}^{S} U_{Mean} \, dS \\
U_{Mean} &= \sqrt{U_x^2 + U_y^2}
\end{align*}
\] (13)

As it can be confirmed from Table 3, even for a considerable change in mesh size across both directions, \(T_{avg}\) and \(U_{avg}\) show small differences among all grid arrangements. In addition to the averaged quantities, \(Nu_{local}\) distribution is also observed at all the considered grid arrangements as shown in Fig. 4. Based on this examination, Grid 4 is used throughout the present work to maintain an optimum balance between the numerical accuracy and the computational cost.

Furthermore, a validation study is carried out to verify the reliability of the results obtained from the numerical model.
Since the present analysis deals with the influence of non-uniform magnetic field on the hydro-thermal characteristics of a ferrofluid, a similar problem statement is considered for the validation as shown in Fig. 5. Ganguly et al. [8] studied the forced convection of a hot ferrofluid over an isothermal wall at different \( Re \) along with magnetic dipoles of various strengths. The distribution of \( Nu_{\text{local}} \) is compared across the bottom wall at \( Re = 11.8 \) for two different dipole strengths \( (m^* = 0 \text{ and } m^* = 0.19) \) as shown in Fig. 6. In the absence of a dipole, a typical exponentially decaying profile is obtained for \( Nu_{\text{local}} \) distribution. However, \( m^* = 0.19 \) displays a local peak followed by a trough that is attributed to the recirculation zone created because of KFD. From Fig. 6, it can be confirmed that the present numerical model exhibits comparable agreement with the literature.

### 3.3 Computational details

The computations for all the governing equations in the present work have been performed within a C++ based open-source framework OpenFOAM 5.0 [41] which uses a finite volume based discretization method. The resulting set of algebraic equations are solved by using various iterative techniques along with different schemes. The Generalised Algebraic Multi Grid solver is used for solving the symmetric matrices, whereas the asymmetric matrices are handled by smoothSolver. The diffusion terms in the governing equations are discretized with the help of a second order accurate central difference scheme and an upwind biased scheme is used for convective terms. For temporal discretization, a backward differencing schemes is used which is also a second order accurate in time. Additionally, the pressure - velocity coupling is achieved with the help of PIMPLE algorithm which is a combination of SIMPLE and PISO [42].
4 Results & discussions

To understand the influence of varying locations and magnetic dipole strengths on the TMC, all 9 arrangements are analysed for their hydro-thermal behaviour at global as well as at local scales. Globally, the magnitude of $U_{\text{Mean}}$ and $\text{Nu}_{\text{avg}}$ is compared among all the configurations as shown in Figs. 7 and 8, respectively. The $U_{\text{Mean}}$ is computed for the complete domain, whereas the $\text{Nu}_{\text{avg}}$ is defined only for the inner hot wall. It can be observed from both aforementioned figures, the magnitude of $\text{Nu}_{\text{avg}}$ as well as the $U_{\text{Mean}}$ increases with the increment in $Mn$ at all dipole locations. However, at all three $Mn$, the maximum $U_{\text{Mean}}$ is obtained for case A, whereas case C has the largest $\text{Nu}_{\text{avg}}$. To understand the reasoning for this complex global behaviour, it is essential to observe the flow characteristics at regional scales. Thus, further local insights are obtained by comparing the $U_{\text{Mean}}$ contours and streamline distribution along with a reference case of $Mn = 0$ at $Ra = 10^6$.

The effect of the different dipole locations at the highest $Mn$ is shown in Fig. 9. In the absence of a magnetic dipole, the streamlines exhibit a typical buoyancy driven flow characteristics. The fluid adjacent to the inner wall retains higher temperature ($T_H$) relative to its surrounding fluid. Such comparably less denser fluid moves in the upward direction creating a clockwise (CW) plume within the ferrofluid domain as shown in sub-figure 9a. However, an existence of a non-uniform magnetic field from the magnetic dipole results in the presence of KFD (as discussed in Sect. 3.1). Such unbalanced body forces disturb the afore-stated typical arrangement and lead to the formation of local vortices. This phenomenon can be clearly noticed from the sub-figure 9b–d where recirculation zones are present within the entire domain at all three dipole locations. Most notably, a large CW recirculation is observed at the top for the case A and an anti-clockwise (ACW) recirculation is noticed at the bottom of semi-circular annulus for case C. The strength of both aforementioned vortices is relatively larger than case B and can be clearly confirmed from the magnitudes of $U_{\text{Mean}}$ contour. Such strong recirculation zones also improve the overall heat transfer by enhancing the ferrofluid mixing which subsequently increases $\text{Nu}_{\text{avg}}$ as compared to case B for all $Mn$. At location B however, alternate CW and ACW vortices at the local scale nullify each others contribution which result in the lower global values for both $U_{\text{Mean}}$ and $\text{Nu}_{\text{avg}}$ as shown in Figs. 7 and 8, respectively. Further, the combined outcome of CW vertical plume from the buoyancy force and a CW recirculation at the top results in the highest $U_{\text{Mean}}$ magnitudes for case A at all $Mn$. On the other hand, the presence of relatively longer recirculation zone along with the larger $U_{\text{Mean}}$ magnitude is responsible for the maximum $\text{Nu}_{\text{avg}}$ observed at location C.

On the similar lines, the influence of $Mn$ on the flow distribution of TMC is compared for the case B as shown in Fig. 10. The presence of magnetic dipole at $\theta = 0^\circ$ lead to the major flow disturbances near the central region at all $Mn$. It is
to be noted that the number of recirculation zones increases with the increase in $Mn$, as shown in sub-figure 10b–d. This significant observation is attributed mainly to the presence of KFD that elongates the distinct CW vertical plume of the buoyancy driven flow. This stretching of the recirculation zone results in the formation of a smaller pair of CW vortices (refer sub-figure 10b). With the further increase in $Mn$, such smaller vortices eventually separate and develop in their size. This local observation justifies the increased global values of $U_{\text{Mean}}$ and $\text{Nu}_{\text{avg}}$ with respect to $Mn$ at all dipole locations as demonstrated in Figs. 7 and 8.

To further complement our understanding about the hydrodynamic interactions of TMC, isotherms and $\text{Nu}_{\text{local}}$ distributions are also observed for all configurations. As shown in Fig. 11, influence of the strength and the location of the magnetic dipole is compared for all cases along with a reference case of $Mn = 0$ at $Ra = 10^6$. For the aforementioned reference case, a typical thermal plume is obtained at the top of annulus as shown in sub-figure 11a. Further, for the same case of pure natural convection ($Mn = 0$), the $\text{Nu}_{\text{local}}$ distribution follows a decreasing linear trend with maxima at the bottom of the inner hot wall (at $\theta = -90^\circ$) (Figs. 12 and 13). Such peculiar distribution of local $Nu$ and isotherm can also be confirmed from the seminal works of Kuehn and Goldstein [43] and Abu-Nada et al. [44] where exactly similar results are reported for natural convection.

On the other hand, it is identified that the presence of magnetic dipoles affects the overall thermal distribution within the domain. For case A (sub-figure 11b–d) and case B (sub-figure 11f–h), the lower half of the annulus exhibits smaller temperatures. However, relatively larger magnitude of $T$ is present throughout the domain for location C (sub-figure 11j–l), resulting in the improved values of local (Fig. 12) as well as average $Nu$ (Fig. 8) at all $Mn$. Also, analogous to the streamlines, all isotherms exhibits major variations in the vicinity of their corresponding dipole location. To be specific, even for smallest $Mn$, improved thermal performance is noticed along the inner hot wall in the upper half for case A (sub-figure 11b), near the centre for case B (sub-figure 11f), and in the lower half for case C (sub-figure 11j). This behaviour subsequently leads to the presence of local peaks in the $\text{Nu}_{\text{local}}$ distribution at different $\theta$ corresponding to its dipole location as shown in Fig. 12. In addition to the local peaks, the minute undulations of case B signifies the chaotic nature of the flow structures present within the domain. Moreover, as discussed earlier, the presence of increased recirculation zones at higher $Mn$ eventually improves the heat transfer from the inner hot wall to the surrounding ferrofluid. This specific finding can also be confirmed from the Fig. 13, where proportional increment of $\text{Nu}_{\text{local}}$ peaks is observed with the increase in $Mn$ for case B.
Fig. 11  Variation of isotherms for different locations and $Mn$, where $Mn^*, Mn^{**}, Mn^{***}$ corresponds to $Mn = 6.433 \times 10^{10}$, $Mn = 2.573 \times 10^{11}$ and $Mn = 1.029 \times 10^{12}$, respectively.
A ferrofluid based Thermo-Magnetic Convection is numerically investigated in the present work for a differentially heated semi-circular domain. Flow and thermal response is analysed by observing $U_{\text{Mean}}$, isotherms, and streamlines along with the local and global $Nu$ distribution. Overall, it is observed that the magnetic dipole stimulates the formation of flow vortices that significantly alter the hydro-thermal interactions within the ferrofluid. Such modifications are found to be highly dependent on the dipole location and its magnitude. At any specific location, increased number of recirculation zones are noticed at higher $Mn$. As a result of this, the magnitudes of both $Nu_{\text{avg}}$ and $U_{\text{Mean}}$ increases with $Mn$ and their highest values are observed for location C and location A, respectively. Additionally, the presence of localised peaks is noticed in the $Nu_{\text{local}}$ distribution corresponding to its dipole location. This specific finding strongly advocates the possibility of using magnetic dipoles to control and enhance the thermo-hydraulic performance of the heat exchangers.

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Declarations

Conflicts of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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