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Investigating the effects of a non - uniform magnetic field on heat and flow characteristics of a ferrofluid

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Abstract. A numerical study is performed to investigate the effect of a non - uniform magnetic field from a current carrying wire on the ferrofluid flow. The analysis is carried out for a semi circular annulus with three different locations of wire relative to it, by solving coupled set of flow field equations, energy equations and the Maxwell's magnetostatics equations. Results from the present study offers better insight about the ferrofluid behaviour and heat transfer mechanism. It also explains the dependency of flow distribution on the location of the electric wire and the magnitude of current flowing through it.

1. Introduction

Because of their distinct thermophysical and magnetic properties, ferrofluids are being widely used to regulate as well as to enhance the heat and flow characterstics [1, 2]. Various studies [3] have been performed by researchers to investigate the mechanism of Thermomagnetic Convection (TMC) using a non - unifom magnetic field from different sources such as permanent magnet, electromagnet, and electric wires. Aminfar et al. [4, 5] carried out a numerical analysis to study the effect of magnetic field from a wire on ferrofluid flow within a rectangular and a helical duct respectively. Vatani et al. [6] did experimental as well as numerical analysis of ferrofluid surrounding an electrically heated vertical wire. Additionally, many authors also discussed the influence of non uniform magnetic fields from a current carrying wire on biomagnetic fluid flows [7, 8, 9]. In general, all the above studies concluded that non - uniform magnetic field alters the velocity profile which ultimately affects the Nusselt number distribution inside the ferrofluids.

The present study aims to investigate the influence of a non-uniform magnetic field distribution on combined natural convection and TMC within a semi-circular annulus. For observing the flow behaviour, streamlines are compared along with averaged Nusselt number (Nu_{avg}) magnitude among all the configurations.

2. Problem Description and Computational Methodology

For the present analysis, a water based colloidal suspension of 5% of volume fraction (ϕ) of Fe_3O_4 particles is considered as the working fluid. This ferrofluid is present within a 2-D semi-circular annulus of a fixed L/D ratio of 0.8, where L is the width of annulus ($L = Ro - Ri$) and D represents the internal diameter. An electric wire is assumed to carry a constant current of known magnitude in the perpendicular plane and is placed at a radial distance of $0.75Ri$ in three different orientations ($\theta = 60°$) as as shown in Figure 1. All the thermophysical

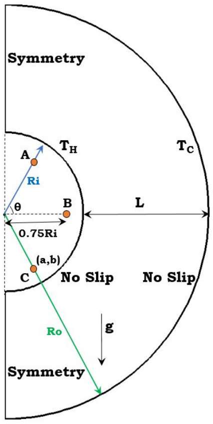


Figure 1. Geometrical representation of the present case.

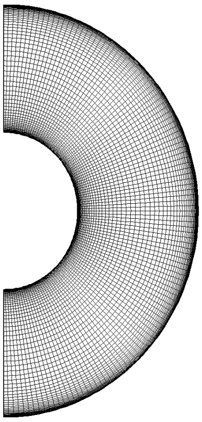


Figure 2. Grid distribution of the entire domain.

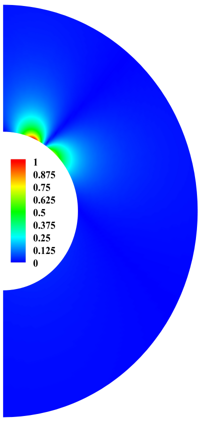


Figure 3. H^* distribution for location A.

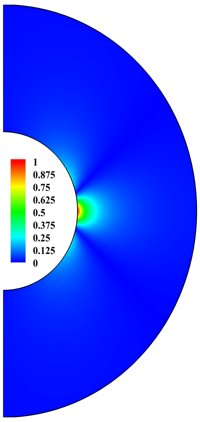


Figure 4. H^* distribution for location B.

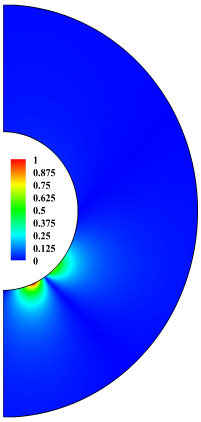


Figure 5. H^* distribution for location C.

properties for ferrofluid ($\rho_{nf}, C_{pnf}, \mu_{nf}$, and k_{nf}) are modelled in accordance with the equations and values mentioned in Fadaei et al. [10]. The simulations are carried out for a fixed Ra ($Ra = g\beta(T_H - T_C)L_c^3/\nu_{nf}\alpha_{nf}$) of 10^6 and three different magnitudes of Mn ($\mu_0 H_r^2 L_c^2/\rho_{nf}\alpha_{nf}^2$ where $H_r = I/2\pi b$). The domain is discretised into a structured non - uniform grid with fine meshing near both the walls (Figure 2). The non-dimensionalised distributions of the strength of magnetic field ($H^* = H/H_{max}$) for all three locations are shown in Figures 3 -5.

The components of H are modelled as a function of their coordinates in Cartesian form [7]. For the sake of brevity, only momentum equation of a laminar, incompressible, and transient newtonian fluid is mentioned here (Equation 1) and the boundary conditions are provided in Table 1. The continuity equation, energy equation, and Maxwell's equation for an electrically non conducting medium can be referred from Vatani et al. [6].

Momentum Equation

$$\rho_{nf}\frac{D\mathbf{U}}{Dt} = -\nabla p + \mu_{nf}\nabla^2\mathbf{U} + \mu_0\left(\mathbf{M}\cdot\nabla\right)\mathbf{H} + g(\rho_{nf} - \rho_\infty) \tag{1}$$

To calculate the Kelvin body force ($\mu_0\left(M\cdot\nabla\right)H$), the magnetisation of ferrofluid is modelled with the superparamagnetic magnetisation law [11] as shown in Equation 2.

Magnetisation Equation

$$\mathbf{M} = M_d\phi\left[coth(\alpha) - \frac{1}{\alpha}\right] \quad \text{where } \alpha = \frac{\mu_0 m H}{K_b T} \tag{2}$$

As the present analysis deals with the influence of non-uniform magnetic field on flow and heat characteristics, a validation study is carried out to compare the local Nusselt number (Nu_{local}) distribution with Ganguly et al. [12]. It can be clearly observed from Figure 6 that, the present numerical model shows a nice agreement with the published results. Also, to make sure that our model is free of discretization errors, results from five different grid sizes are compared for a case of $Ra = 10^6$ and $Mn = 2.573\times10^{11}$, at the location B. It can be seen from Table 2, even for a considerable change in mesh count, domain averaged magnitudes of temperature (T_{avg}) and velocity (U_{avg}) shows small differences, thus Grid 4 is finalised. All the computations for present work are performed within a C++ based open-source framework OpenFOAM 5.0. [13] where PIMPLE algorithm is used for pressure- velocity coupling.

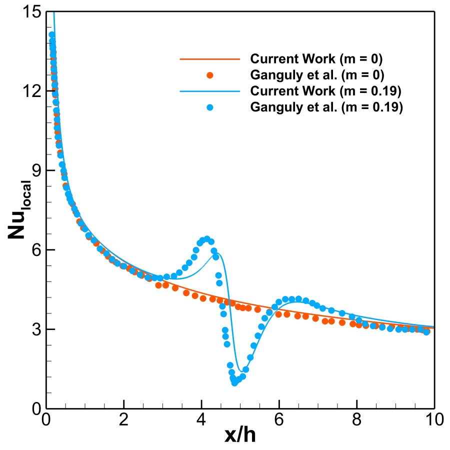


Figure 6. Comparison of Nu_{local} distribution from the present numerical results with Ganguly et al. [12] .

Table 1. Information about Boundary Conditions

	Inner Wall	Outer Wall	Centreline
$\mathbf{U}$	$u, v, w = 0$	$u, v, w = 0$	$\partial \mathbf{U}/\partial n$
T	T_H	T_C	$\partial T/\partial n$

Table 2. Grid Independence Test

	No. of Nodes	T_{avg}	U_{avg}
Grid 1	80 × 40	300.458	1.273×10^{-5}
Grid 2	100 ×50	300.438	2.798×10^{-5}
Grid 3	120 × 60	300.411	2.473×10^{-5}
Grid 4	140 × 70	300.403	2.160×10^{-5}
Grid 5	160 × 80	300.392	1.814×10^{-5}

3. Results and Discussion

To analyse the configurations, magnitudes of mean velocity ($U_{Mean} = \sqrt{U_x^2 + U_y^2}$) and Nu_{avg} are compared for fluid domain and inner hot wall respectively. It is observed that, the magnitude of Nu_{avg} as well as the U_{Mean} increases with the increase in Mn at all the wire locations. To gain further insights, streamlines are plotted for all three positions of wire at highest Mn with a reference case of $Mn = 0$. In the absence of any current, the streamlines displays a typical buoyancy driven flow characteristics where the less denser fluid moves in the upward direction creating a clockwise (CW) plume at the top (Figure 9 (a)). As opposed to this, the non-uniform magnetic field from the current carrying wire will disturb this arrangement and create local vortices. This phenomenon can be clearly noticed from Figure 9 (b) and 9 (d) where small recirculation zones are present at the top (CW) and bottom (ACW) of annulus for location A and C respectively. These recirculations also improve overall heat transfer from the inner hot wall to the surrounding fluid which can be confirmed from Figure 7 where Nu_{avg} has larger magnitudes for location A and C as compared to the location B for all Mn. In contrary to the Nu_{avg}, maximum values for U_{Mean} (Figure 8) are observed at location A, which can be attributed to the combined outcome of vertical plume from the buoyancy force (CW) and local recirculations (CW) from the current carrying wire. For location B, alternate CW and ACW

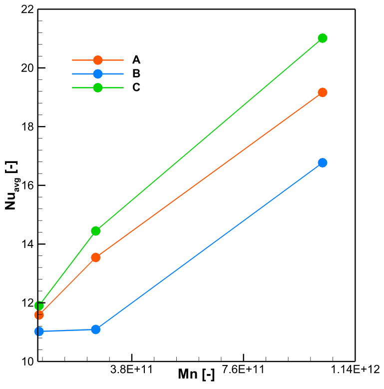


Figure 7. Variation of Nu_{avg} for different positions of wire and Mn.

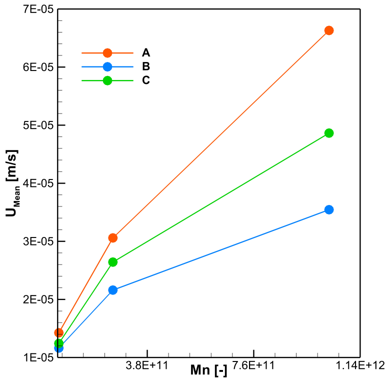
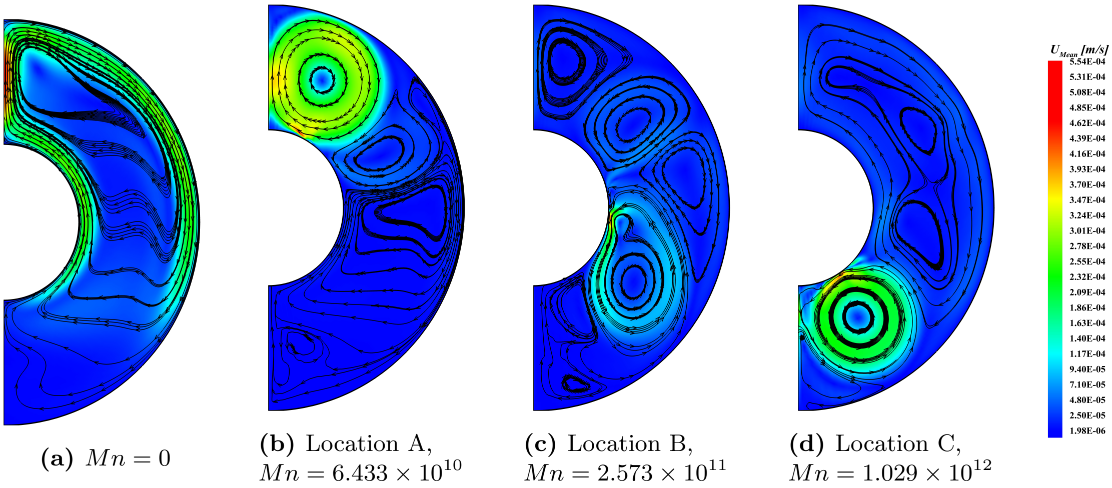


Figure 8. Variation of U_{Mean} for different positions of wire and Mn.



(a) $Mn = 0$ **(b)** Location A, $Mn = 6.433 \times 10^{10}$ **(c)** Location B, $Mn = 2.573 \times 10^{11}$ **(d)** Location C, $Mn = 1.029 \times 10^{12}$

Figure 9. U_{Mean} contours and streamline distribution for $Ra = 10^6$.

vortices nullify each others contribution which result in the lowest values for both Nu_{avg} and U_{Mean}.

4. Conclusion

A numerical study is carried out to explore the influence of an electric wire on heat transfer and flow attributes of a ferrofluid within semi-circular annulus. It is observed that, a current carrying wire can be used as an effective means to control and increase the localised heat transfer within ferrofluids.The magnitudes of both Nu_{avg} and U_{Mean} increases with Mn and their highest values are noticed for location C and location A respectively.

Acknowledgments

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