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Research Article

MAGNETOHYDRODYNAMIC FLOW AND HEAT TRANSFER OF FERROFLUID PASSING THROUGH A CONFINED CYLINDER

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ABSTRACT. The present investigation numerically studied the hydrothermal behaviors of a ferrofluid with a mixture of water and Fe_3O_4 solid particle of 2% volume concentration over a circular cylinder settled in a confined straight channel experienced with non-uniform magnetic field throughout current transporting wires. The ferrofluid inside the confined channel is assumed as a single phase with volume fraction, Φ=2% and laminar while two symmetrical wires with respect to the channel axis are chosen as a magnetic source. The effects of Hartmann number, *Ha*, which denotes the magnetic field severity, Reynolds number, *Re* on the boundary layer detachment and normalized velocity distribution, *u/U* together with heat transfer enhancement factor, *EF* are explored utilizing Ansys Fluent 20 package program. When the magnetic field is applied non-uniformly, the flow structure turns into to steady case from an unsteady pattern for Hartmann number, *Ha*≥10 and separation length, L_s reduces at *Re*=150 due to the magnetic field induced Lorentz forces which provides extra durability to the ferrofluid flow and damps mainstream flow. According to the results of numerical simulation, the distribution and maximum value of normalized streamwise velocity component, $u/U\infty$ attenuate as Hartmann number, *Ha* grows in the range of 0≤*Ha*≤18 since non-uniform magnetic field opposes fluid dynamics and ferrofluid flow motion. Obtained results demonstrated that the heat transfer enhancement factor, *EF* always improves with increase in the Hartmann number, *Ha* at *Re*=25 and 50. This increment is in the vicinity of 17% at *Re*=25 and 8% at *Re*=50 when *Ha* augments from *Ha*=6 to *Ha*=14

Keywords: *Confined cylinder, Enhancement factor, Hartmann number, Non-uniform magnetic field, MHD flow*

INTRODUCTION

The research on the flow and thermal characteristics of confined cylinders has a widespread application field such as cooling of electronic components, chemical processes. Due to the such important applications, the flow structure and thermal performance of cylindrical objects placed in closed channel have been widely studied from past to present [1-4].

Heat exchangers have a crucial importance in industrial and engineering applications and augmenting the efficiency of these heat exchangers has been a topic that gets attention from researchers and scientists. There are different heat transfer techniques such as passive methods and active methods. In passive heat transfer enhancement techniques, the augmentation of heat transfer is acquired by modifying the geometry of the channel [5-7] or mixing the base with solid additives [8,9]. The modifying channel geometry aims to increase the surface area in which heat transfer takes place and to augment heat transfer by enhancing the fluid mixing. In active heat transfer improvement techniques, the enhancement of mixing can be acquired by disturbing of flow with external forces. The most familiar heat transfer improvement techniques utilized by investigators can be summarized as magnetic and electrostatic fields, pulsating flow, acoustic waves and synthetic jets.

Magnetohydrodynamic (MHD) flows are applied in broad industrial and engineering implementations. The application area of MHD flows can be summarized as metallurgical operations, materials science, flow meters and casting processes that include the conducting fluid and magnetic field application. Morley et al. [10] stated that the self-cooled blankets of fusion reactors and the cooling circuits of fast fission reactors are impressive applications of MHD flow in industrial field. The MHD flow applications are intriguing and requested because of the association of familiar flow hydrodynamics equations with Maxwell's expressions. The Lorentz force appears in x and y momentum equations because of the non-uniformly applied magnetic field and induces several nonlinearities.

The investigations about the flow of ferrofluid over the confined cylindrical body placed a rectangular channel with a magnetic field effect have an important role in comprehensive engineering implementations. Dousset and Potherat [11] numerically investigated the influence of the strong magnetic field applied parallel through the cylinder axis on the 2-D liquid metal flow in a square channel. This study demonstrated that the linear friction term which is proportional to the ratio of the Reynolds number, *Re* to the Hartmann number, *Ha* is a very effective parameter for the control of the transition of the flow region. Moreover, it has been stated that the 2D vortex street breakdown takes place at the Reynolds number of Re=5000. Yoon et al. [12] described the critical interaction parameter, N as the Stuart number which turns unsteady fluid flow and thermal fields into steady ones. The oscillation amplitude of flow and thermal parameter reduces with increasing the Stuart parameter, N in the region where $N<N_{cr}$, eventuate in reducing lift coefficient, C_L and the Strouhal number, *St*. Moreover, the separation point moves toward the rear side of the cylinder and the width of the wake field gets narrower with raising Strouhal, *St* number within the region of $N>N_{cr}$. According to Udyakumar et al. [13], it was revealed that while there are two symmetrical, but counter-rotating foci in other words circulating flow bubbles with respect to the axis of the cylinder in forced convection, the symmetrical flow structures disrupt in mixed convection heat transfer without applied magnetic field. But the imposed magnetic field enhances the symmetrical structure of the flow in mixed convection. They pointed out that the imposed magnetic field is beneficial in terms of suppressing flow separation and controlling heat convection. The main observations from the work of Tassone et al. [14] are that the applied magnetic field suppresses the wake of the cylinder and hence the thermal performance is detected to augment with increasing *Ha* and inclination angle. Moreover, pressure drag as well as the heat transfer rate is noticed to change non-monotonically by increasing inclination angle of the applied magnetic field. In the numerical investigation of Ishak et al. [15] which is about the effect of applied magnetic field on the flow and heat transfer properties in the region outside of a stretching cylinder, the value of skin friction coefficient is found to grow by increasing the intensity of the magnetic field.

Even though many investigations have been reported related to the uniformly employed magnetic field effect on the hydrothermal attitudes of nanofluids, the search on the influence of non-uniformly employed magnetic field is very constricted. Additionally, a few reported documents are present about the non-uniformly applied magnetic field which influences flow in different channels such as rib channel [16], T-junction [17], semi-insulated horizontal pipe [19], sinusoidal channel [18], while no investigation has been reported regarding the effectiveness of non-uniform magnetic field over the confined cylindrical body. Lee and Kim [20] concluded that the natural convection heat transfer performance of the ferrofluid inside the enclosure is improved with a non-uniformly applied magnetic field due to the occurrence of the vorticity concentrations in the enclosure to create a separated flow circulation zone. Izadi et al. [21] numerically studied the free convection of a hybrid nanofluid exposed to a non-uniform magnetic field. According to them, the Nusselt number, *Nu* is substantially reduced by raising the Hartmann number, *Ha* and at the greater Rayleigh number, *Ra* due to the reduced power of the flow. They stated that the increase in *Ha* weakens the vorticity and reduces deformation of isothermal lines, putting the isothermal lines into a flatter form. In the numerical study of Ghasemian et al. [22], acquired results revealed that while constant magnetic field enhances the heat transfer mechanism by 16.48% at Re=25, this enhancement grows up to 27.72% as the alternating magnetic field is performed with the same magnetic field strength at magnetic field frequency, f=4 Hz. They pointed out that the heat transfer augmentation because of the magnetic field application worsens with increasing *Re*. Sheikholeslami et al. [23] pointed out that the increase in *Ha* causes the thickness of the thermal boundary layer to be increased while it reduces with the increase in *Re*. According to them, the influence of nanoparticle addition is more notable at higher Hartmann numbers compared to lower ones. Sheikholeslami and Vajravelu [24] revealed that the temperature gradient grows by the increase in the volume fraction of nanofluid and this increment is more notable in the existence of applied magnetic field. According to them, the influence of the increment of nanofluid volume fraction becomes weaker when convective heat transfer gets higher.

The objective of the present investigation is numerically to study the hydrothermal behaviors of a ferrofluid with a mixture of water and Fe_3O_4 solid particle of 2% volume concentration over a cylindrical object settled in a confined straight channel experienced with a non-uniform magnetic field throughout current transporting wires. Though some studies have been documented related to the uniformly employed magnetic field influences on the hydrothermal attitudes of nanofluids, the numerical simulations related to the impact of the non-uniform magnetic field is highly constricted. Additionally, some reported documents can be observed about the employment of non-uniform magnetic field influences on different channels such as rib channel, T-junction, semi-insulated horizontal pipe, and sinusoidal channel while any work is not recorded regarding the effectiveness of non-uniform magnetic field over the cylindrical body settled in a straight channel. Thus, the current study will be the first investigation regarding the impact of a non-uniformly employed magnetic field on the hydrothermal properties of a ferrofluid over the circular cylinder settled in a straight channel.

MATERIALS AND METHODS

Problem description and related mathematical expressions

The simulation domain includes a rectangular channel with a heated circular cylinder settled from the channel inlet as L_1=12D and from the channel outlet as L_2=18D as demonstrated in Fig. 1. The circular cylinder is settled on the channel's central axis with a blockage ratio, $BR=D/H$ of 0.3. The upper and lower walls of the channel are regarded as adiabatic with the no-slip condition, u=v=0. The parabolic velocity profile is carried out at the channel inlet with the equation of, $u = 6BRy\,(1 - BRy)$. The pressure at the channel outlet is regarded as zero, P=0. Fig.1 displays the flow domain demonstration of the where the ferrofluid flow is regarded from inlet section towards outlet section. In this figure, F and R represent the front and rear stagnation points, respectively.

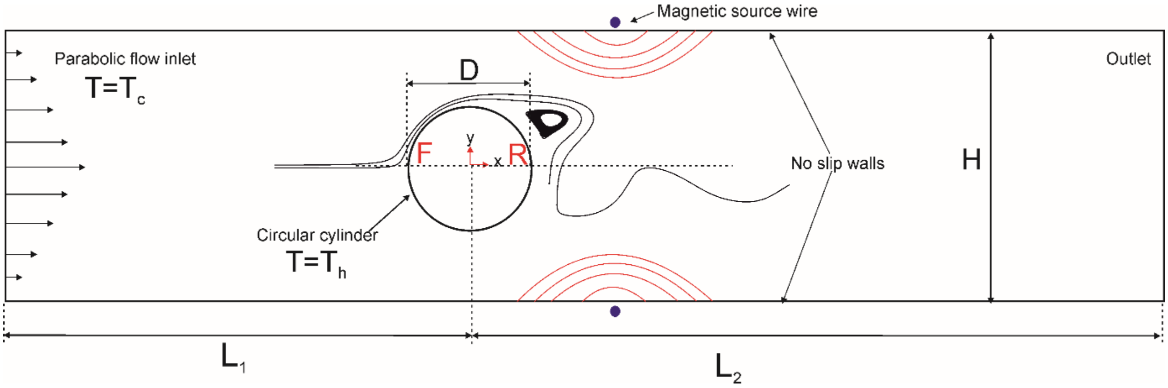

Fig.1. *The flow domain demonstration of the ferrofluid and the indication of basic parameters of ferrofluid flow on the confined cylinder*

The ferrofluid flow is regarded as 2D, and the physical features of the ferrofluid is regarded as fixed and the influence of radiation is disregarded. The mathematical expressions of Continuity, X-momentum, Y- momentum and Energy equations are demonstrated in Eqns. (6), (7), (8) and (9), respectively, in the subsequent forms;

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0 \tag{6}$$

$$\rho_{ff}\left(\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}}\right) = \frac{-\partial \bar{p}}{\partial \bar{x}} + \mu_{ff}\left(\frac{\partial^2 \bar{u}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{u}}{\partial \bar{y}^2}\right) - \sigma_{ff}\left(\left[B_y^2 + B_{yy}^2\right]\bar{u} - \left[B_x B_y + B_{xx} B_{yy}\right]\bar{v}\right) \tag{7}$$

$$\rho_{ff}\left(\bar{u}\frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{v}}{\partial \bar{y}}\right) = \frac{-\partial \bar{p}}{\partial \bar{x}} + \mu_{ff}\left(\frac{\partial^2 \bar{v}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{v}}{\partial \bar{y}^2}\right) - \sigma_{ff}\left(\left[B_x^2 + B_{xx}^2\right]\bar{v} - \left[B_x B_y + B_{xx} B_{yy}\right]\bar{u}\right) \tag{8}$$

$$(\rho Cp)_{ff}\left(\bar{u}\frac{\partial T}{\partial \bar{x}} + \bar{v}\frac{\partial T}{\partial \bar{y}}\right) = k_{ff}\left(\frac{\partial^2 T}{\partial \bar{x}^2} + \frac{\partial^2 T}{\partial \bar{y}^2}\right) \tag{9}$$

In Eqns. (7) and (8), the expressions of $-\sigma_{ff}\left(\left[B_y^2 + B_{yy}^2\right]\bar{u} - \left[B_x B_y + B_{xx} B_{yy}\right]\bar{v}\right)$ and $-\sigma_{ff}\left(\left[B_x^2 + B_{xx}^2\right]\bar{v} - \left[B_x B_y + B_{xx} B_{yy}\right]\bar{u}\right)$ represent the Lorentz force per unit volume along x and y directions, respectively and occur due to the electrical conductivity of ferrofluid. They are common in magnetohydrodynamics

implementations.
The Hartmann number which denotes the non-uniform magnetic field strength is calculated based on the Eqn. (10) as;

$$Ha = DB_0\sqrt{\frac{\sigma_{bf}}{\mu_{bf}}},$$

where D is the cylinder diameter, B_0 is the magnetic field induction, σ_{bf} is the electrical conductivity of the base fluid and μ_{bf} is the base fluid dynamic viscosity. In this investigation, heat transfer enhancement factor, *EF* is computed as the ratio of the average Nusselt number, Nu_{avg} during the existence of non-uniformly applied magnetic field to Nu_{avg} for no magnetic field case, Ha=0. The average Nusselt number, Nu_{avg} is calculated based on the following Eqn. (11):

$$Nu_{avg} = \frac{1}{w}\int_0^w Nu_L\, dW \tag{11}$$

In Eqn. (11), Nu_L denotes the local Nusselt number on the cylinder surface and it is denoted as in Eqn. (12):

$$Nu_L = -\left(\frac{k_{ff}}{k_{bf}}\right)\frac{\partial\theta}{\partial n}\bigg|_w \tag{12}$$

in which n and w express the vertical direction to the wall and the wall cylinder's whole length, respectively.

The *EF* at Ha=z can be calculated based on the following Eqn. (13):

$$EF = \frac{Nu_{avg,Ha=z}}{Nu_{avg,Ha=0}} \tag{13}$$

The ferrofluid (Fe_3O_4-water) employed as the working fluid, and the volume fraction of the solid particle, Fe_3O_4 in the ferrofluid are taken as Φ=2%. The ferrofluid in the flow domain is regarded as single phase and the constant thermophysical features are handled and they are demonstrated in Table 1 as;

***Table 1**. Thermophysical values of ferroparticles and water.*

	Water	Fe_3O_4
Density, $\boldsymbol{\rho}$ **(kg/m^3)**	998.2	5200
Specific heat, $\boldsymbol{C_p}$ **(J/kgK)**	4182	670
Thermal conductivity, $\boldsymbol{k}$ **(W/mK)**	0.6	6
Thermal expansion coefficient, $\boldsymbol{\beta}$ **(1/K)**	2.1×10^{-4}	1.3×10^{-5}

Solution Procedure

In the numerical simulations, the Ansys Fluent package program is utilized to reveal the effect of the non-uniformly employed magnetic field on the hydrothermal attitudes of the ferrofluid in the channel. The User Defined Functions (UDF) module embedded in the Fluent package problem is used to create source terms presenting the impact of the non-uniformly applied magnetic field

The grid generation of the computational flow domain over the confined cylinder is displayed in Fig. 2. As one can see from this image, the density of grid generation is greater in the vicinity of the cylindrical body and channel walls.

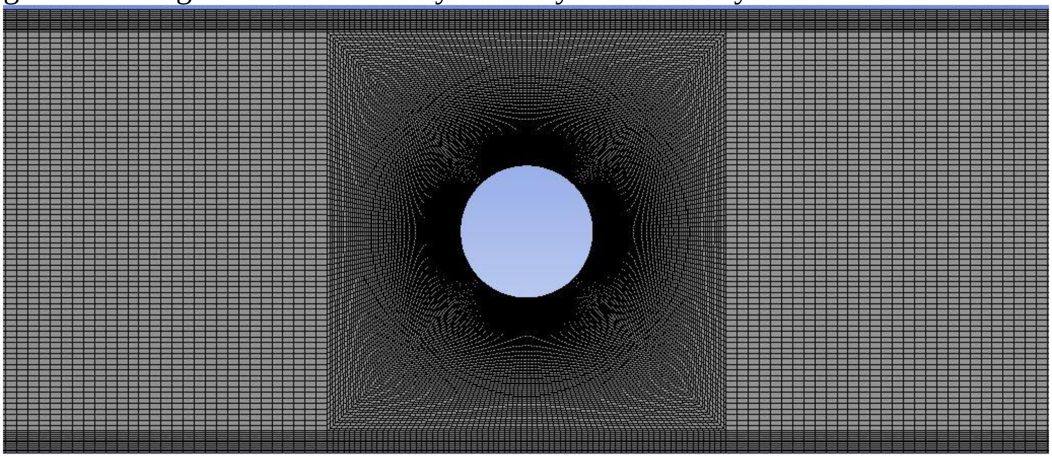

Fig.2. *Grid generation of computational flow domain over the confined cylinder and channel walls*

A mesh independency control is carried out to make sure that the numerical results are not influenced by the element number of grids. Four different meshes with growing grid sizes from 16302 to 87024 are regarded. Figure 3 shows the average Nusselt number and drag coefficient for each mesh size.
The acquired data presented in Fig. 3 demonstrated that the percentage error between mesh elements of 63936 and 87024 is nearly 0.004% for average Nusselt number and 0.07% for drag coefficient. Thus, grid generation with 63936 elements size is considered for the numerical simulations in this article.

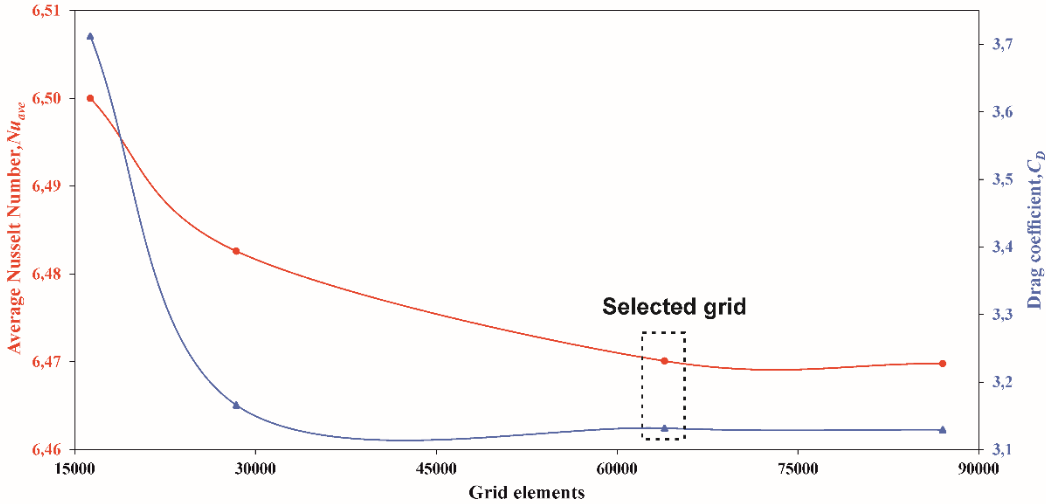

Fig.3. *Outcomes of mesh independency check at Re = 100, for BR= 0.3*

The numerical results presented in this study were validated with the data of Prasad et al [25]. The results are in very good agreement between this study and the validated study for the variation of Nusselt number at different Reynolds number, *Re* for *BR*=0.1 as shown in Fig. 4 (a) and for *BR*=0.3 as in Fig. 4 (b). Furthermore, the non-uniform magnetic field implementation is validated with the investigation of [24] at *Ha*=10 as presented in Fig.5. As resulted from this Figure, the trend and consistency of these compared works are acceptable.

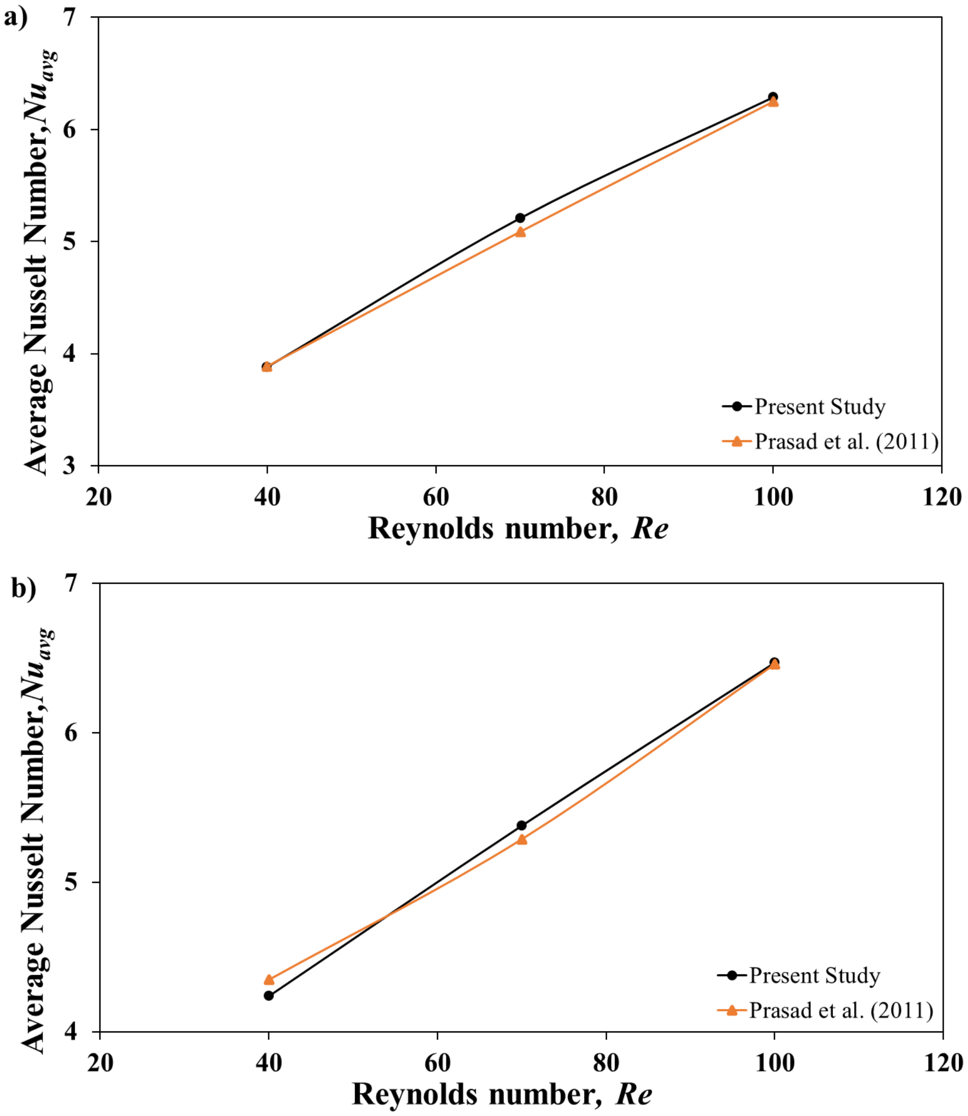

Fig.4. *The validation process for confined cylinder with a) BR=0.1 b) BR=0.3*

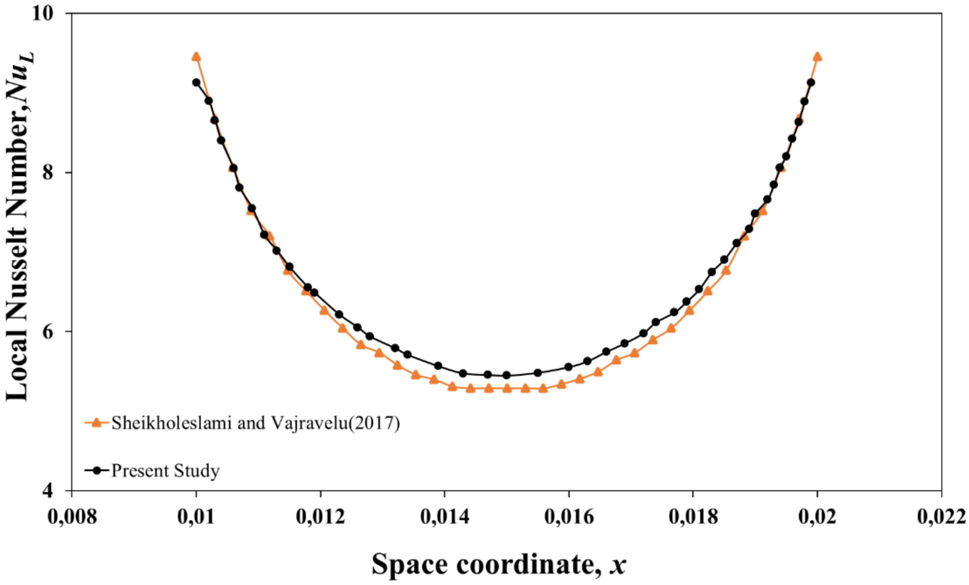

Fig.5. *The validation study of current investigation with the outcomes of [24] at Ha=10*

RESULTS AND DISCUSSION

The change of streamline distribution over the cylinder surface with *Ha* is depicted in Figs. 6 and 7 for *Re*=50 and 150, respectively. In these figures, *Ha*=0 denotes the absence of non-uniform magnetic field application. At *Ha*=0 and *Re*=50, the steady pattern of the ferrofluid is observed with two symmetric vorticities in the wake field downstream of the cylinder. In Fig.6, L_s is the separation length which is a distance between reattachment point and back stagnation point in the flow direction. Our findings show that the grow in *Ha* causes the reduction of separation length, L_s. For instance, whereas the separation length, L_s corresponds to the normalized streamwise distance, *x/D*= 2.137 at *Ha*=0, this value reduces to *x/D*= 1.22 and 0.6831 for *Ha*=6 and 14, respectively. As a result, one can infer that separation point occurs in the closer region of the rear stagnation point with a rise in *Ha* due to the squeezing effect of the non-uniform magnetic field going through current-carrying wires.

It is apparent in Fig.7, the flow is an unsteady state with alternate shed of vorticities from the cylinder surface at *Re*=150 and *Ha*=0. Moreover, the flow is still time-independent at *Ha*=2 and 6, the beyond rise in *Ha* to *Ha*=10 renders unsteady flow case to steady case with a closed wake region. When the *Ha* changes from *Ha*=10 to *Ha*=14 and then *Ha*=18, the recirculation bubble length, L_s decreases from the normalized streamwise distance, *x/D*=1.37 and 1.1, respectively. The flow structure variation from unsteady patterns to steady patterns and reduction of the separation length can be dependent on the non-uniform magnetic field induced Lorentz forces and thus periodic vortex shedding is weakened and separation length, L_s is reduced. Besides, Lorentz forces provide extra durability to the ferrofluid flow and act as a damping force that suppresses any instabilities in the flow domain.

According to Figs. 6 and 7, the two symmetric clusters of vorticity are observed in the confined channel near the current carrying wires because of the non-uniform magnetic field application. These vorticity concentrations become visible at *Ha*=10 for *Re*=50 and *Ha*=14 for *Re*=150 and their size gets smaller when Reynolds number is increased from *Re*=50 to *Re*=150. It should be noted that the two symmetric vorticities caused by the magnetic inductions are effective on the enhancement factor (*EF*) increment with non-uniform magnetic field which will be discussed in Fig.10.

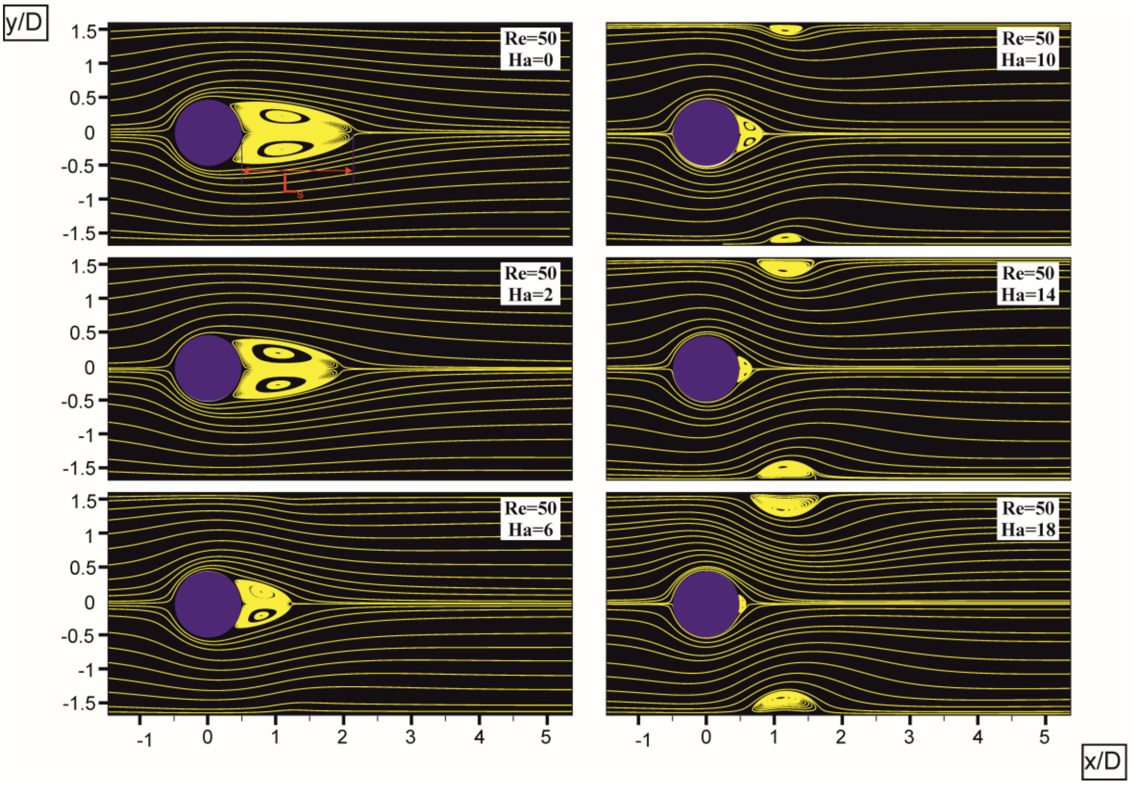

Fig. 6. *The influence of Ha on the variation of streamline patterns around the cylindrical object at Reynolds numbers, Re=50 and Φ=2%*

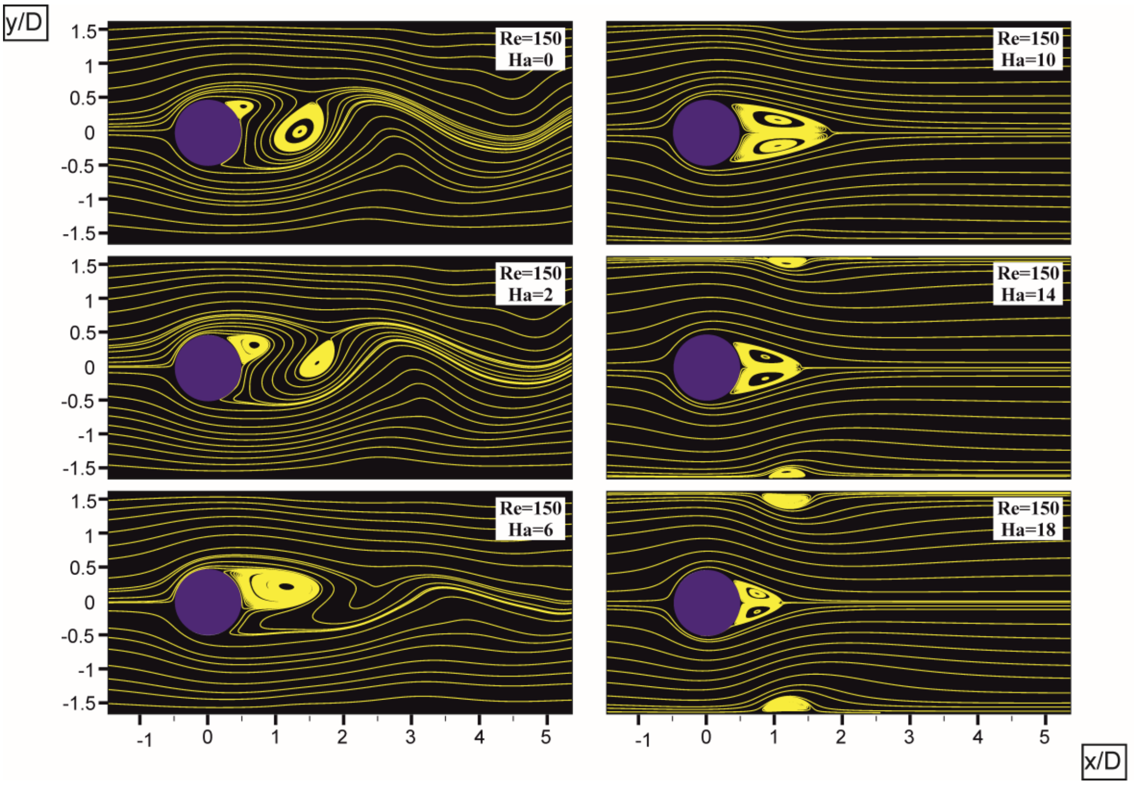

Fig. 6. *The influence of Ha on the variation of streamline patterns around the cylindrical object at Reynolds numbers, Re=150 and Φ=2%*

The impact of the *Ha* on the normalized streamwise velocity distribution, u/U_∞ around the confined cylindrical object is represented in Figs. 8 and 9. As seen in Fig.8, the wake field behind of the cylindrical object gets narrower when the *Ha* is introduced, and its intensity grows from *Ha*=0 to *Ha*=18 gradually. Furthermore, the strength of velocity distribution in the vicinity of non-uniform magnetic field application point weakens with increasing *Ha*. Since Lorentz forces, which occur due to the application of a non-uniform magnetic field and proportional to the magnetic field strength, are acting straightly to dump the freestream velocity component. The velocity of nanofluid flow gets lower with increasing magnetic field strength. According to Fig.9, the unsteady pattern of velocity distribution over the cylinder becomes a steady state when *Ha* goes up from *Ha*=0 to *Ha*=10 at *Re*=150. Obtained results demonstrate that the time-dependent flow structure turns into time-independent structure with increasing magnetic field intensity at *Re*=150. The distribution and maximum value of normalized streamwise velocity component, u/U_∞ attenuates as *Ha* grows in the range of 0≤*Ha*≤18 since the non-uniform magnetic field opposes the fluid dynamics and nanofluid flow motion. Besides, in steady flow regime, as *Ha* rises from *Ha*=10 to *Ha*=18, the extent of the wake flow region rear of the cylinder weakens. Here, it should be noted that the applied non-uniform magnetic field influences the temperature distribution and heat transfer rate of the conductive fluid indirectly by changing the distribution of ferrofluid velocity.

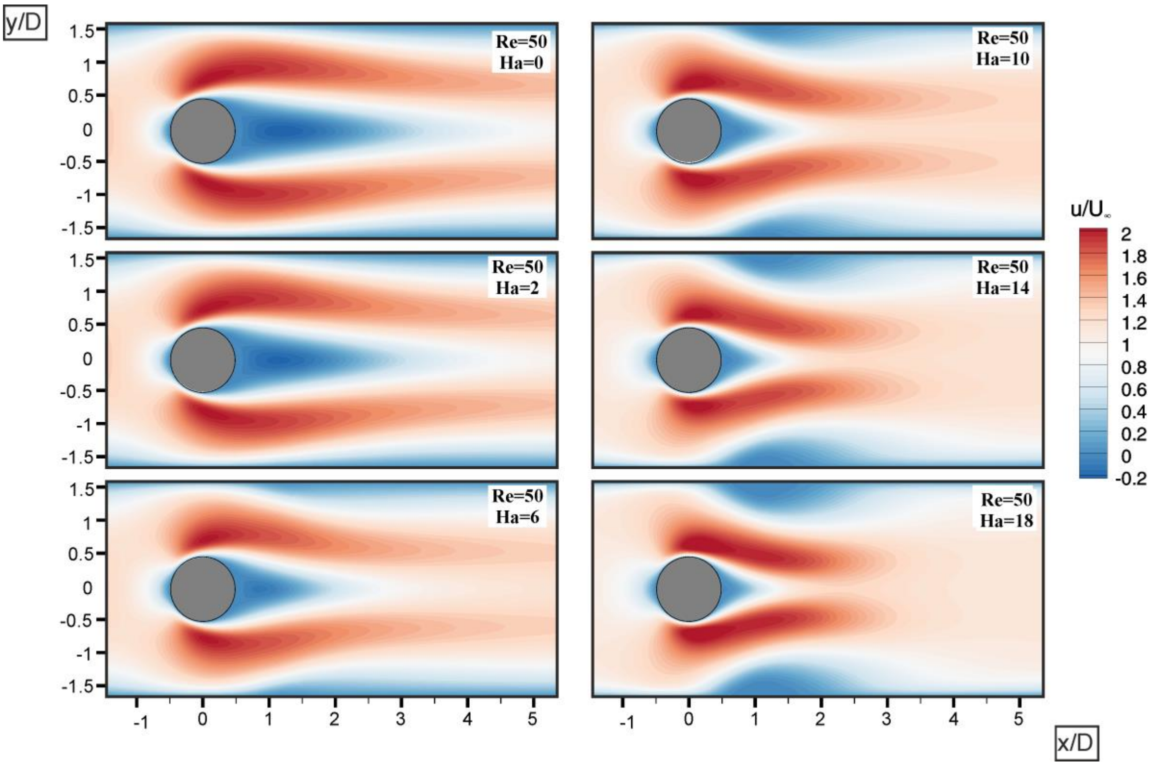

Fig. 8. *The influence of Ha on the variation of streamwise velocity contours, u/U_∞ around the cylinder at Reynolds numbers, Re=50 and Φ=2%*

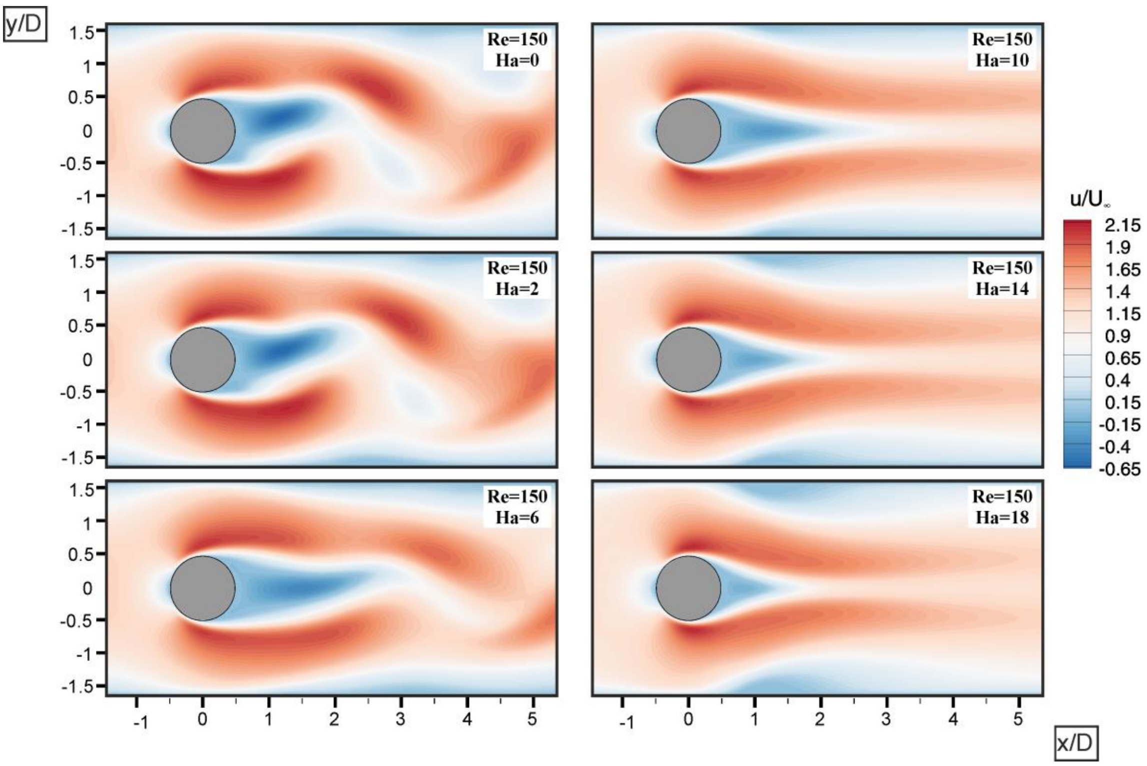

Fig. 9. *The influence of Ha on the variation of streamwise velocity contours, u/U_∞ around the cylinder at Reynolds numbers, Re=150 and Φ=2%*

Fig. 10 shows the effect of *Ha* on the heat transfer enhancement factor (*EF*) at *Re*=25,50,100 and 150. Here, *EF* is defined as the ratio of Nu_{avg} for the existence of magnetic field application, in other words, *Ha* greater than zero, *Ha*≥0 to the Nu_{avg} for no magnetic field case, *Ha*=0. As seen in Fig. 10, the *EF* always improves with increasing Hartmann number, *Ha* at Re=25 and 50. For example, *EF* gets higher from *EF*=1.045 to *EF*=1.232 which corresponds to a 17% increment when *Ha* goes up from *Ha*=6 to *Ha*=14. On the other hand, at *Re*=50, heat transfer enhancement factor, *EF* increases from *EF*=0.998 to *EF*=1.083 which corresponds to an 8% increment when *Ha* augments from *Ha*=6 to *Ha*=14. Obtained results demonstrate that the increase in *EF* deteriorates with increasing *Re* since the effect of *Ha* weakens at greater *Re* as seen in streamline patterns demonstrated in Figs. 6 and 7. The augmentation of *EF* with increasing *Ha* can be attributed to the enhanced Nu_{avg} by non-uniform magnetic field due to the decreasing thermal boundary layer thickness, and increasing temperature gradient over the surface of the cylindrical object. Moreover, the improvement of *EF* with the implementation of a non-uniform magnetic field can be attributed to the occurrence of two symmetric vorticity concentrations in the rectangular channel near the region where the magnetic source is employed non-uniformly. It should be noted the heat transfer enhancement factor, *EF* is not usually improved or deteriorated with introducing and then increasing *Ha*. Generally, the strong magnetic field intensity such as *Ha*=10,14,18 and 22 causes the *EF* to be augmented at *Re*=100 and 150. For other Hartmann numbers, *Ha* the *EF* deteriorates with increasing the intensity of the magnetic source. This observation can be indicated by considering the result that the flow pattern is the steady state at *Ha*=0 and 2 for *Re*=100, and *Ha*=0, 2 and 6 for Re=150. The periodic vortex shedding from the cylinder surface in a time-dependent flow pattern augments thermal performance as these vortices transfer momentum and heat to other regions of the flow field. In time-independent flow region, the intensity of vortex shedding weakens with growth in *Ha*, thus Nu_{avg} worsens. As a result, the *EF* attenuates by reducing Nu_{avg} in the existence of magnetic induction.

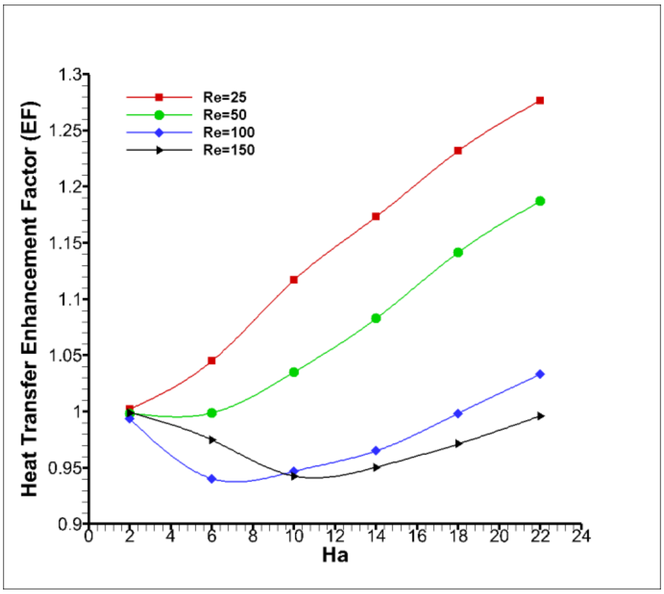

Fig. 10. *The influence of Ha on the variation of heat transfer enhancement factor (EF) at Re=25, 50, 100 and 150 for Φ=2%*

CONCLUSION

A numerical investigation is carried out to explore the impacts of the non-uniformly employed magnetic induction on the flow behaviors and enhancement factor, *EF* of a ferrofluid with Φ=2% in the rectangular channel with cylindrical body. In this study, the UDF module of the Ansys Fluent package program is carried out to obtain magnetic field.

The most important results are summarized as follows: It has been detected that the separation length, L_s corresponds to the normalized streamwise distance, *x/D*=2.137 at *Ha*=0, while it reduces to *x/D*=1.22 and 0.683 for *Ha*=6 and 14, respectively at *Re*=50. The strength of the velocity distribution in adjacent region of the non-uniform magnetic field application point weakens with increasing Hartmann number, *Ha* due to the effect of Lorentz forces. The extent of wake domain at the rear of the cylinder gets narrower when *Ha* is introduced and its intensity is augmented. The enhancement factor, *EF* always augments with increasing *Ha* at *Re*=25 and 50 while this is not the case at greater *Re* such as, *Re*=100 and 150.

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