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Experimental Investigation on Laminar Forced Convective Heat Transfer of Ferrofluid under Different Modes of Magnetic Field.

دراسة عملية لانتقال الحرارة بالحمل الجبري الرقائقي لمائع مغناطيسي تحت تأثير أنماط مختلفة من المجال المغناطيسي.

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KEYWORDS:
Ferrofluid, Forced convection, Heat transfer enhancement, Constant magnetic field, Alternating magnetic field, Rotating magnetic field

الملخص العربي:- **يقدم البحث دراسة عملية لتأثير المجال المغناطيسى الثابت والمتردد والدوار علي انتقال الحرارة بالحمل لمائع نانو مغناطيسي (خليط الماء وجزيئات اكسيد الحديد Fe_3o_4) (Ferrofluid) وذلك خلال نمط السريان الرقائقي في انبوبة من النحاس ذات تسخين منتظم في منطقة السريان كامل التطورهيدروليكيا. تم تصميم وبناء نظام مغناطيسي رباعي الأقطاب (Quadrupole system) وذلك لتوليد كل من المجال المغناطيسي الثابت والمتردد والدوار. تم دراسة انماط تشغيل مختلفة للمجال المغناطيسي واختيار النظام الأعلي كفاءة. أجريت التجارب باستخدام مائع نانو مغناطيسي ذو تركيز كتلي 2.5%. تم اختبار تاثير تغير كل من التردد وسرعة الدوران وذلك في حالة المجال المغناطيسي المتردد والدوارعلي الترتيب. أظهرت التجارب الابتدائية فاعلية النظام أحادى القطب (Uni-pole system) فى تحسين انتقال الحرارة بالحمل مقارنة بالانظمة الأخري. لوحظ تحسن واضح في معامل انتقال الحرارة بالحمل للمائع المغناطيسي تحت تأثير المجال المغناطيسي الثابت حيث تحسن معامل انتقال الحرارة بالحمل تحت تأثير المجال المغناطيسي الثابت بنسبة 119.6% وذلك لمائع نانو مغناطيسي ذو تركيز 2.5% عند (Re = 2000). انخفضت نسبة التحسين إلي 106.7% و 96.8% وذلك عند استخدام المجال المغناطيسي الدوار والمتردد علي الترتيب. أظهرت النتائج أيضا أن زيادة كل من تردد المجال المتردد وسرعة المجال الدوار أدت إلي انخفاض نسبة تحسين معامل انتقال الحرارة بالحمل.**

***Abstract*— In this paper, the effects of constant, alternating and rotating magnetic fields on the laminar forced convective heat transfer of Fe_3o_4/water nanofluid (ferrofluid) in a uniformly heated copper tube are investigated experimentally. The local convective heat transfer coefficients are measured in the hydrodynamically fully developed region. The experiments are conducted using ferrofluid with 2.5% mass concentration. A quadrupole magnetic field system has been designed and constructed to generate the constant, alternating and rotating magnetic fields. For the magnetic field system, different operation modes were also examined and the most efficient mode was obtained. The effects of alternating magnetic field frequency and rotating magnetic field speed were also studied. The primary experiments showed that Uni-pole magnetic field system provides the maximum heat transfer enhancement. A significant enhancement in the local convective heat transfer of ferrofluid was observed by application of constant magnetic field. It was observed that constant magnetic field has provided a maximum local heat transfer enhancement of 119.6% compared to the case without magnetic field for ferrofluid with 2.5% mass concentration and at Re = 2000. This value is decreased to 106.7% and 96.8% by application of rotating and alternating magnetic field, respectively. Additionally, increasing the alternating magnetic field frequency and the rotating magnetic field speed adversely affect the heat transfer enhancement.**

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I. INTRODUCTION

Ferrofluid is a stable colloidal mixture of single-domain magnetic nanoparticles (magnetite, ferric oxide, iron nickel oxide, etc.) dispersed in a nonmagnetic carrier fluid, such as water or oil. Similar to the other magnetic materials, magnetic nanoparticles could be controlled and manipulated by using an external magnetic field. Application of external magnetic fields makes it possible to control fluid flow and heat transfer characteristics of ferrofluids. Consequently, ferrofluids exhibit both fluid and magnetic properties. Such unique characteristics of ferrofluids in the presence of magnetic field attract the attention of many researchers in the recent years. Several studies have focused on the thermal conductivity of ferrofluids in the presence of magnetic field [1-4]. Philip et al. [1] observed 300% enhancement in the thermal conductivity of Fe_3o_4/water nanofluid in the presence of magnetic field. Also, Gavili et al. [2] reported 200% enhancement in the thermal conductivity of Fe_3o_4/water nanofluid in presence of magnetic field.

Recently, few published studies investigate the forced convective heat transfer characteristics of ferrofluids in the presence of magnetic field. Motozawa et al. [5] studied experimentally the effect of constant magnetic field on heat transfer of a magnetic fluid named W-40 in a rectangular duct. They observed that the heat transfer coefficient increases locally in the region where magnetic field exists and the heat transfer enhancement increases by increasing magnetic field intensity. They reported a maximum of 20% enhancement in heat transfer coefficient in the presence of magnetic field. Lajvardi et al. [6] examined the convective heat transfer of ferrofluid flowing through a heated copper tube in the laminar regime in the presence of magnetic field. They observed a significant enhancement in the heat transfer coefficient under the effect of an applied constant magnetic field. The increase in heat transfer coefficient is attributed to the improvement in ferrofluid thermo physical properties under an influence of magnetic field. Azizian et al. [7] studied the laminar convective heat transfer and pressure drop of magnetite nanofluids flow in a uniformly heated tube under the effect of an external magnetic field. Their results showed a significant enhancement (up to 300%) in the local heat transfer coefficient of magnetite nanofluids with a low penalty to the pressure drop when a magnetic field was applied. On the contrary, Ghofrani et al. [8] showed that the application of constant magnetic field adversely affects or has low enhancement in the convective heat transfer.

The previous mentioned studies have focused on the application of constant magnetic field to enhance heat transfer in ferrofluids. The effect of alternating magnetic field on heat transfer was also examined by other researchers [8-11]. Ghofrani et al. [8] conducted an experimental investigation on the forced convection heat transfer of ferrofluid flow in a circular copper tube in the presence of an alternating magnetic field. They observed a maximum of 27.6% enhancement in the convection heat transfer at low Reynolds numbers when the alternating magnetic field was used. Goharkhah et al. [9] investigated the effects of constant and alternating magnetic field on the laminar forced convective heat transfer of Fe_3o_4/water nanofluid in a uniformly heated tube. They observed an enhancement in heat transfer up to 18.9% and 31.4% by application of constant and alternating magnetic field, respectively. They indicated that migration of nanoparticles to the tube surface increases local thermal conductivity which enhances heat transfer in the case of constant magnetic field. Additionally, disruption of the thermal boundary layer and increased flow mixing were assumed to be the possible reasons for the heat transfer enhancement by application of alternating magnetic field. Goharkhah et al. [10] studied the laminar forced convective heat transfer of Fe_3o_4/water nanofluid in uniformly heated channel under an alternating magnetic field. They reported a maximum heat transfer enhancement of 24.9% and 37.3% by application of constant and alternating magnetic field, respectively. Shahsavar et al. [11] studied the effects of constant and alternating magnetic fields on the laminar forced convective heat transfer of Fe_3o_4/CNT hybrid nanofluid. They reported an enhancement in the heat transfer coefficient with the application of constant and alternating magnetic fields. Moreover, they showed that the heat transfer enhancement is more significant in the case of constant magnetic field compared to alternating magnetic field which is contradictory to other studies [8-10].

The number of studies on the forced convective heat transfer of ferrofluids in presence of magnetic field is still limited and in need of more study. As mentioned above, there are some differences in the results of the forced convective heat transfer of ferrofluids under both constant and alternating magnetic fields. Consequently, further researches are required. Most previous studies have used the same u-shaped magnetic field arrangement in their experimental investigations [8-11]. Therefore, the study of different magnetic field arrangements is an important issue. For this purpose, a quadrupole magnetic field system was designed and constructed. Three different operation modes have been considered in the examination of the quadrupole magnetic field system. The most efficient mode was selected according to the primary experiments. Moreover, the design of quadrupole magnetic field allows examining the rotating magnetic field effect on heat transfer. The aim of the current study is to investigate the laminar convective heat transfer for ferrofluid in the presence of a quadrupole magnetic field system. The effects of constant, alternating and rotating magnetic fields are investigated. Different frequencies and rotating speeds are examined for alternating and rotating magnetic field, respectively.

II. EXPERIMENTAL METHOD

A. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. It consists of a flow loop which includes nanofluid reservoir, pump, test section, cooling section, control valves, magnetic field generation and control system, temperature sensors, a data logger system for temperature measurements and a flow meter. Figure 2 presents a photo of the experimental setup.

1) Test section

The main part of the experimental setup is the tube test section. The test section is a straight copper tube of 2000 mm length, 8 mm inside diameter and 9.5 mm outside diameter.

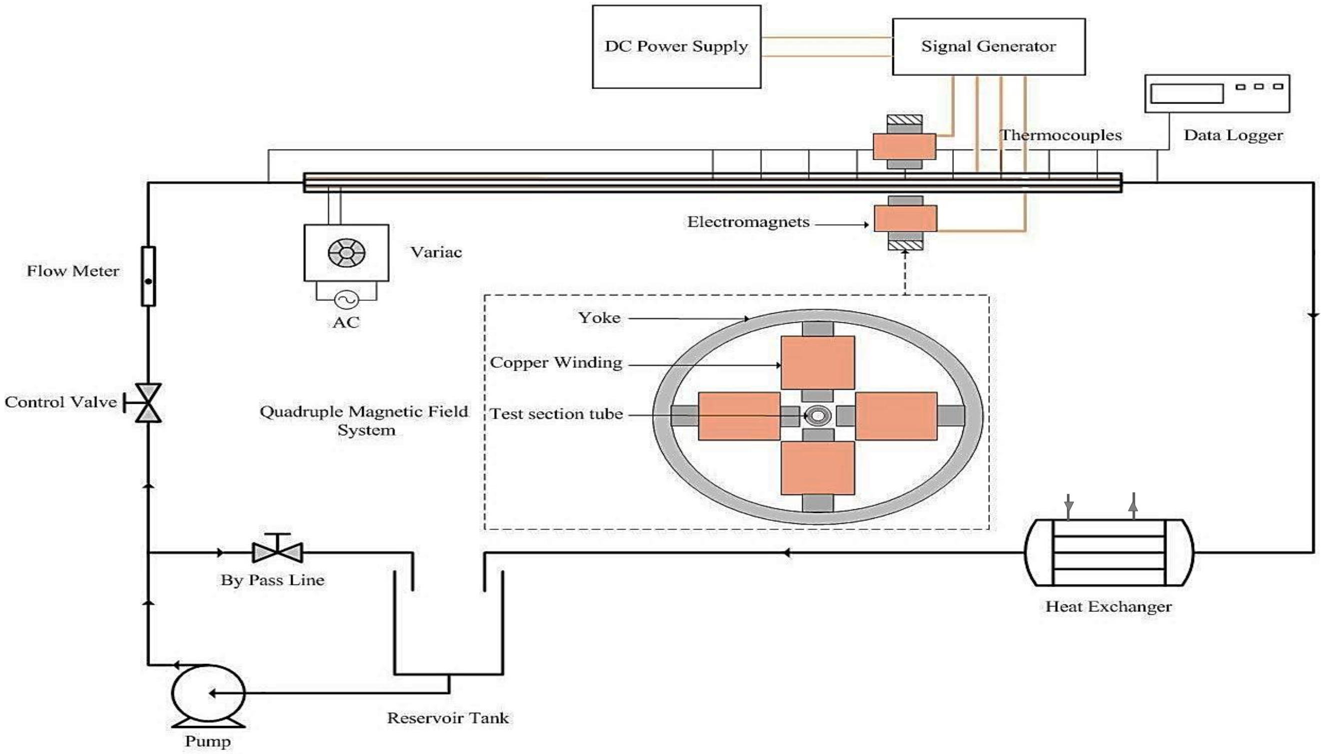


Fig. 1. Schematic diagram of the experimental setup.

The first part of the tube is used as calming section to assure hydro dynamically fully developed flow in the rest part of the tube. The calming section has 1000 mm length. The rest part of tube represents the actual test section which is 1000 mm in length. An electric heating element was uniformly wounded around the tube to maintain a uniform heat flux along the tube. The heating element is connected to a power supply system which is controlled to get the required heat flux along the tube. The wire of the heating element was isolated electrically from the tube to avoid short circuit. The electric heater doesn’t contain any ferric material to avoid distortion of the magnetic field inside the tube. The first 50 mm and the last 50 mm of the tube lengths are kept unheated to eliminate the end effects in temperature measurements. Two plastic bushings are connected to the inlet and the outlet of the copper tube to minimize heat flow in the axial direction. Nine thermocouples were distributed along the test section and connected to outer tube wall to measure the wall temperature. The thermocouples are mounted on the test section at axial positions in mm of 1000(T1), 1100(T2), 1200(T3), 1300(T4), 1400(T5), 1500(T6), 1600(T7), 1700(T8), 1800(T9) from the tube inlet. The whole tube was insulated to minimize radial heat loss. Two thermocouples were used to measure bulk fluid temperatures at the tube inlet and outlet. The two thermocouples are inserted into the flow through the plastic bushings. The thermocouples are connected to a data logger to record the output of all thermocouples.

Fluid flow loop

A centrifugal pump has been used to circulate the fluid through the flow loop. The out flow from the test section passes through a cooling system. A cooling system is used to cool down the fluid after the test section and maintain steady state condition through the test section. This was achieved by a cooling section which uses water as a cooling medium. After passing through the cooling section, the fluid is then returned to the reservoir. A by-pass line with a control valve is put after the pump to adjust the flow rate through the system. A gate valve was used to control the flow rate through the test section. A rotameter was used to measure the fluid flow rate through the test section.

2) Magnetic field generation system

The magnetic field generation system consists of electromagnets, a control system and a DC power supply. A control system has been designed to control electromagnets supplying current. With the help of the control system, different effects of magnetic field could be generated. The control system has the ability to generate constant, alternating and rotating magnetic fields. A teslameter was used to measure the magnetic flux density. Moreover, an oscilloscope has been used to show the pulse wave shape generated from the control system in the case of alternating and rotating magnetic fields.

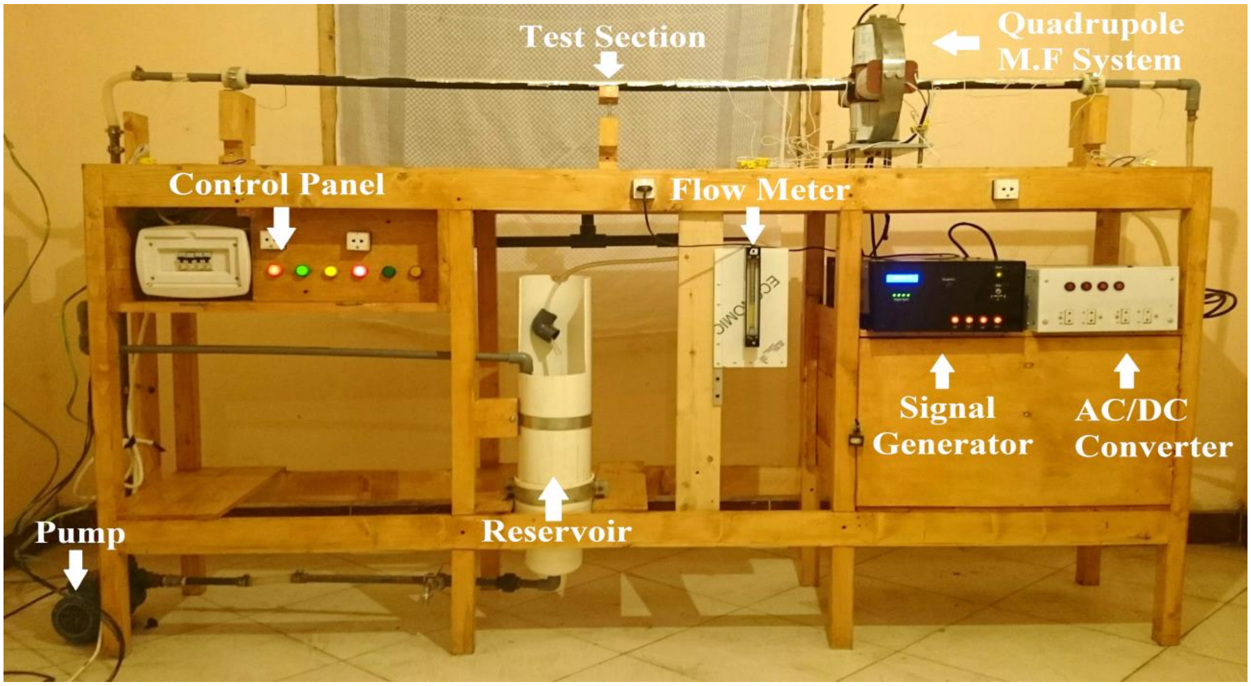


Fig. 2. Photo of the experimental setup.

3) Quadrupole magnetic field system

The magnetic field system consists of four identical electromagnets. The four electromagnets are arranged perpendicular to each other. This system is called quadrupole magnetic field system. As shown in Fig.1, the quadrupole magnetic field system is located at a distance x = 1400 mm from the tube inlet at the thermocouple (T5). The four electromagnets are connected to the power supply such that each pole is surrounded by two poles of different polarity. Figure 3 illustrates the construction and operation of the quadrupole magnetic field system. The resulted magnetic field is axisymmetric through the tube cross section. The magnetic field intensity increases in the radial direction towards the tube wall. As shown in Fig. 3(b), the quadrupole system can exert a uniform radial force to the particles towards the tube wall. The magnetic field force could attract the particles towards the tube wall where the electromagnets exist.

The quadrupole system consists of a yoke holding four identical electromagnets, as shown in Fig. 3(a). The yoke is made from short iron cylinder. The yoke has 310 mm inside diameter, 335 mm outside diameter and 50 mm length. The yoke has been used to complete the magnetic field circuit. Each electromagnet includes an iron core and a copper winding, as shown in Fig. 3(a). The iron core is a plate with dimensions (25 mm (H) ×50 mm (W) × 139 mm (L)). Each winding has 3000 turns of 0.8 mm diameter copper wire.

4) Magnetic field control system

A control system has been designed to control the electromagnets supplying current. The control system is connected to a DC power supply. It consists of a signal generator and storage unit. The signal generator has been designed to convert the direct current to rectangular pulses at different frequencies. The signal generator could produce frequencies ranging from 2 HZ to 40 HZ. With the help of signal generator, constant, alternating and rotating magnetic fields could be generated. Moreover, the control system and the DC power supply could provide the required current density and direction in each electromagnet. The signal generator consists mainly of a microcontroller, isolation circuit and electronic power switches circuit. It has four output terminals. Each terminal is connected to an electromagnet.

5) Constant magnetic field

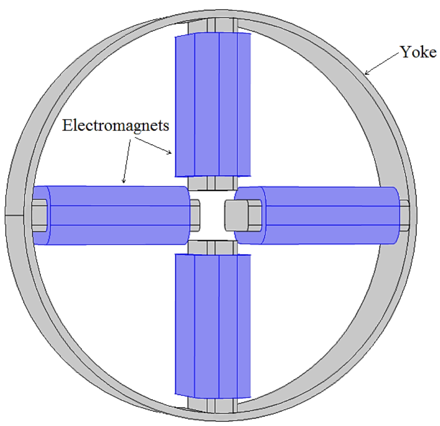
In order to generate a constant magnetic field, the four electromagnets are permanently connected to the DC power supply. For this purpose, the electronic power switches are permanently kept on connection mode. The control system has been designed to provide the required current density and direction in all electromagnets. Therefore, the required magnetic field intensity and direction in electromagnets could be generated.

6) Alternating magnetic field

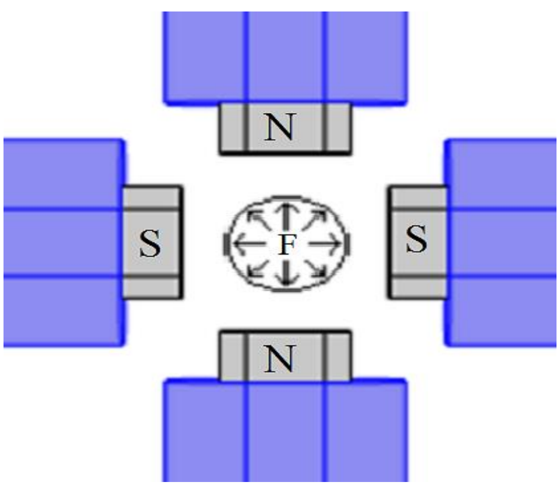
The signal generator has been designed to generate alternating current. It converts the DC current to rectangular pulses. The resulted magnetic field is also an alternating one. The rectangular pulse has equal connection and disconnection time. The frequency of the alternating current is the reciprocal of the connection or disconnection time. The signal generator has the ability to produce the required frequency of the alternating current and the required current density. With the help of the signal generator, different frequencies of 2, 5, 10, 20 and 40 HZ have been investigated. An oscilloscope has been used to show the pulse wave shape as shown in Fig. 4.

7) Rotating magnetic field

In order to generate a rotating magnetic field, the signal generator generates a rotating electric pulse in the four output terminals in sequence. As the four electromagnets are connected to the output terminals, the generated magnetic field is a rotating magnetic field. Moreover, the signal generator has the ability to control rotating pulse speed and so, the rotating magnetic field speed. It worth mentioning that the connection and disconnection time for any electromagnet aren't equal in the case of the rotating magnetic field. The disconnection time equals three times the connection time. Different rotating speeds of 60, 150, 300, 600 and 1200 rpm have been investigated using the signal generator.



(a)



(b)

Fig. 3. Quadrupole magnetic field system: (a) construction and (b) magnetic force distribution.

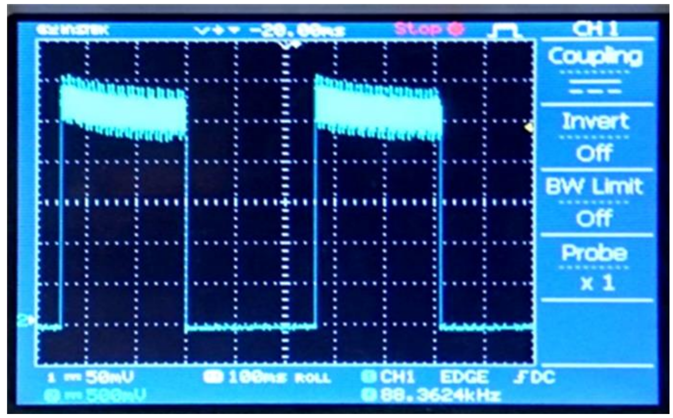


Fig. 4. The shape of the alternating magnetic field wave using an oscilloscope.

TABLE I
PROPERTIES OF Fe_3O_4 NANOPARTICLES.

Purity	Color	Morphology	Average particle diameter (nm)	Density (kg/m³)
98%	Dark brown	Spherical	20-30	4800-5100

B. Ferrofluid preparation and characterization

The magnetite Fe_3O_4 nanoparticles were purchased from US Research Nanomaterial's, Inc. The Fe_3O_4 nanoparticles properties are presented in Table 1. Transmission electronic microscopy (TEM) image of Fe_3O_4 nanoparticles is shown in Fig. 5. The nanoparticles have a mean particle diameter of 20-30 nm. The Fe_3O_4 nanoparticles were dispersed in DI-water to prepare samples of 2.5% mass concentration. The nanoparticles are PVP coated which easier to be dispersed. PVP is Polyvinylpyrrolidone which serves as chemical surfactant to prevent aggregation of nanoparticles resulted from Van der Waals forces and magnetic interaction between the particles. To prevent any nanoparticles agglomerates, the mixture was then sonicated by ultrasonic vibrator (model Vibra-cell, vcx-750). Good mixture stability has been observed and no sedimentation occurred for long time. The nanofluid was sonicated for 30 min before experiments to achieve a stable nanofluid. Finally, the nanofluid was rested for 1h before experiments to avoid any heating effects resulted from ultra-sonication.

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C. Data processing

In order to investigate the heat transfer enhancement, the local convective heat transfer coefficient was obtained. The local convective heat transfer coefficient, $h(x)$, was calculated from the experimental data as follows:

$$h(x) = \frac{q''}{T_S(x) - T_b(x)} \tag{1}$$

Where q'' is the constant heat flux applied to the copper tube and $T_S(x)$ and $T_b(x)$ are the surface temperature and the bulk fluid temperature, respectively. $T_S(x)$ is measured at nine points on the copper tube surface. $T_b(x)$ is obtained from an energy balance on the test section as follows:

$$T_b(x) = T_{bi} + \frac{q''\pi D_o X}{\dot{m} C_p} \tag{2}$$

Where T_{bi} is the fluid bulk temperature at inlet, D_o is the copper tube outside diameter, X is the axial distance from the entrance of the test section, $\dot{m}$ is the fluid mass flow rate and C_p is the fluid specific heat.

The heat flux, q'', has been calculated from the energy conservation along the test section using the following equation:

$$q'' = \frac{\dot{m} C_p (T_{bo} - T_{bi})}{A} \tag{3}$$

Where T_{bo} is the fluid bulk temperature at outlet and A is the tube surface area.

It is worth mentioning that the surface heat flux can also be calculated from the total consumed electric power by the heater from the following equation:

$$q'' = \frac{\mathrm{IV}}{\mathrm{A}} \tag{4}$$

Where I is the measured electric current and V is the supplied voltage. It is very important to show that there is a difference between the heat flux calculated from the energy balance along the test section (Eq. (3)) and that calculated from the experimental measurements (Eq. (4)). This difference is due to the heat losses through the insulation.

The frequency of the alternating magnetic field is defined as:

$$f = \frac{1}{\tau} \tag{5}$$

Where τ is the connection plus disconnection time of the alternating magnetic field which are equal.

For the rotating magnetic field, the rotating speed is defined as [12]:

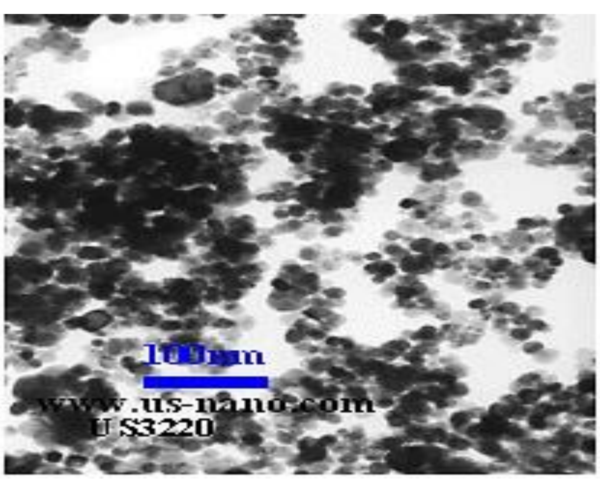


Fig. 5. TEM image of the nanoparticles sample.

$$N = \frac{15}{\tau_c} \tag{6}$$

Where N is the rotating speed of the magnetic field and τ_c is only the connection time for each electromagnet.

D. Uncertainty analysis

The uncertainty of the experimental data arises from the measurement errors of parameters such as temperature, heat flux and length. Table.2 summarizes the accuracies of the measured values in the current study. The uncertainty of the local convective heat transfer coefficient is calculated using the following expression [13]:

$$\omega_Z = \sqrt{(\frac{\partial Z}{\partial Z_1})^2 {\omega_{Z_1}}^2 + (\frac{\partial Z}{\partial Z_2})^2 {\omega_{Z_2}}^2 + \cdots + (\frac{\partial Z}{\partial Z_n})^2 {\omega_{Z_n}}^2} \tag{7}$$

The uncertainty of the local heat transfer coefficient is $\pm$ 8.5%.

TABLE 2
ACCURACY OF THE MEASURED PARAMETERS

Quantity	Uncertainty
T(°C)	$\pm$ 0.5
Voltage (V)	$\pm$ 0.01
Current (A)	$\pm$ 0.001
L (m)	$\pm 5 \times 10^{-4}$

E. Thermophysical properties of the ferrofluid

The volume concentration of the ferrofluid samples, φ, are calculated from the following equation:

$$\varphi = \frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{m_f}{\rho_f}} \tag{8}$$

Where m_p is the mass of particles, m_f is the mass of base fluid, ρ_p is the particle density and ρ_f is the base fluid density.

The density and the specific heat of the ferrofluid are calculated from the conventional mixture laws as follows [14]:

$$\rho_{ff} = \varphi\rho_p + (1 - \varphi)\rho_f \tag{9}$$

$$C_{p,ff} = \frac{\varphi\rho_p C_{p,p} + (1-\varphi)\rho_f C_{p,f}}{\rho_{ff}} \tag{10}$$

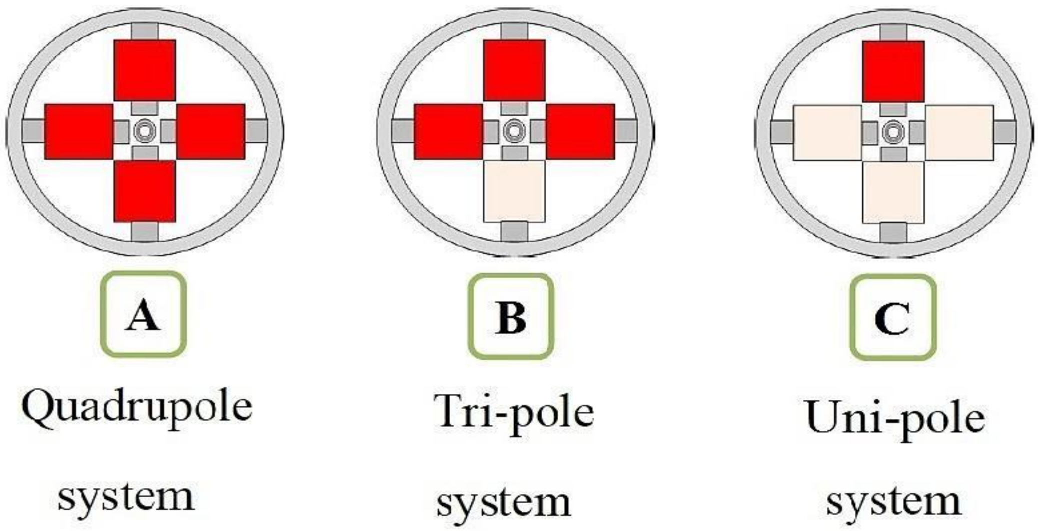


Fig. 6. Schematic diagram for different magnetic field configurations used in primary experiments.

Where $C_{p,p}$ and $C_{p,f}$ are the particle and the base fluid specific heats, respectively.

The viscosity of the ferrofluid is calculated from Brinkman equation [15]:

$$\mu_{ff} = \frac{\mu_f}{(1-\varphi)^{2.5}} \tag{11}$$

Where μ_f is the viscosity of the base fluid.

F. Recognition of the most efficient magnetic field system

Three different configurations have been considered in magnetic field operation according to Fig. 6: Quadrupole system (case A), Tri-pole system (case B) and Uni-pole system (case C). In the case of quadrupole system, the four electromagnets are kept on connection mode such that each pole is surrounded by two poles of different polarity. For Tri-pole system, the upper three neighboring electromagnets are kept on connection mode, while the fourth is disconnected. In the case of Uni-pole system, only the upper electromagnet is kept on connection mode while others are disconnected. Each electromagnet is supplied with a rated current of 1 ampere in all aforementioned cases. Primary experiments are conducted to investigate the convective heat transfer characteristics of ferrofluid using different magnetic field configurations. The most efficient system is selected according to the results of the primary experiments.

III. RESULTS AND DISCUSSION

A. Setup validation

In order to verify the reliability and the accuracy of the experimental setup, the local convective heat transfer coefficients have been measured experimentally for deionized water flow in the tube at two different Reynolds numbers of 1200 and 2000. The experimental results have been compared with those calculated from the well-known Shah equation (Eq. (12)) for laminar flow in a tube under constant heat flux boundary condition [16]:

$$Nu(x) = \begin{cases} 1.302{x_*}^{-1/3} - 1, & x_* \leq 0.00005 \\ 1.302{x_*}^{-1/3} - 0.5, & 0.00005 \leq x_* \leq 0.0015 \\ 4.364 + 8.68(10^3 x_*)^{-0.506} e^{-41x_*}, & x_* \geq 0.0015 \end{cases} \tag{12}$$

Where

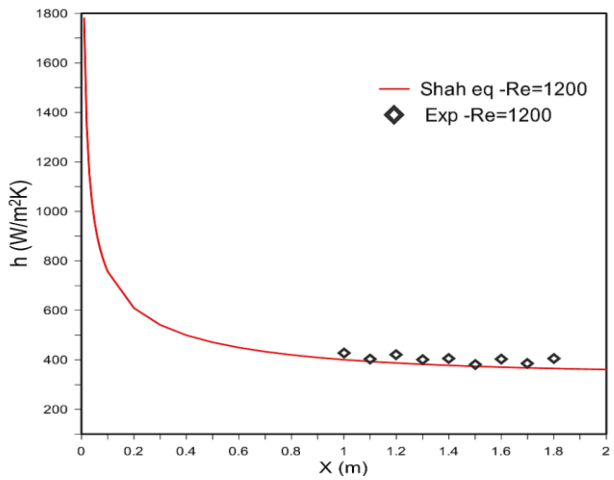
$$x_* = \frac{x/D}{RePr} \tag{13}$$

Figure 7 shows a good agreement between the experimental results and shah equation for deionized water flow in the tube.

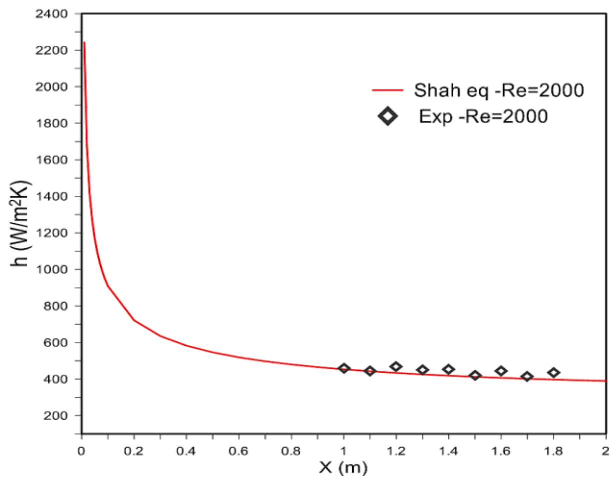
After the validation of the experimental setup, the main experiments were conducted using ferrofluid with mass concentration of 2.5%. Different magnetic field configurations were examined and the most efficient one was selected. Series of experiments were carried out to measure the convective heat transfer coefficient of ferrofluid under the effect of constant, alternating and rotating magnetic fields. For the alternating magnetic field, frequencies of (f = 2, 5, 10, 20, 40 HZ) were studied. Different rotating speeds of (N = 60, 150, 300, 600, 1200 rpm) were investigated in case of the rotating magnetic field. For all experiments, the data are collected in the steady state condition. The steady state condition is reached after 30-60 min.

B. Heat transfer of ferrofluid in the presence of constant magnetic field

First, ferrofluid is prepared at 2.5% mass concentration. As mentioned earlier, primary experiments are conducted to investigate the convective heat transfer characteristics of ferrofluid using different magnetic field configurations presented in Fig. 6. The most efficient system is then selected according to the results of the primary experiments as follows.



(a)



(b)

Fig. 7. Experimental values of the local heat transfer coefficient for deionized water flow compared with shah equation for (a) Re=1200 and (b) Re=2000.

All experiments are conducted using ferrofluid with 2.5 % mass concentration under constant magnetic field at Re=2000. Figure 8 shows a comparison of the local convective heat transfer coefficient in the three magnetic field configurations along with the case without magnetic field. As shown in Fig. 8, the uni-pole system provides the maximum enhancement in the convective heat transfer coefficient compared to the other configurations. A maximum enhancement of 119.6% compared to the case without magnetic field was observed for uni-pole system, while using Tri-pole system and quadrupole system provide 104.5% and 99.3% maximum enhancements, respectively. It is obvious that uni-pole system is the most efficient system then tri-pole system and quadrupole system, respectively.

According to previous studies [8-10], different reasons are thought to be responsible for heat transfer enhancement of ferrofluid under the effect of constant magnetic field. In the presence of constant magnetic field, the magnetic force attracts magnetic nanoparticles to the electromagnets location which causes the migration of nanoparticles towards the tube wall. The magnetic nanoparticles aggregate and start to move over the inner tube surface at electromagnets location which mixes again with the flow after passing the electromagnets. Particle migration towards the tube surface leads to higher local thermal conductivity at the electromagnets location. Moreover, magnetic nanoparticles aggregation near the surface disturbs the boundary layer. Also, Goharkhah et al. [10] proposed that aggregation of nanoparticles near the surface acts like an obstacle that disturb and changes the thermal boundary layer thickness and the flow pattern which result in heat transfer augmentation. Therefore, the increase in the local thermal conductivity and the disturbance of the thermal boundary layer are the possible explanation for heat transfer enhancement of ferrofluids in the presence of constant magnetic field. In the case of quadrupole system, magnetic force causes nanoparticles migration towards the tube surface which covers the whole tube surface near the electromagnets. This keeps the surface away from the fluid flow especially at higher concentrations which may explains the decrease in the heat transfer enhancement in the case of quadrupole system compared to the case of Uni-pole system. This may also explain the decrease in the heat transfer enhancement in the case of the tri-pole system, as the magnetic nanoparticle covers a large region of the tube surface. Therefore, the Uni-pole system has been selected to be used in all experiments.

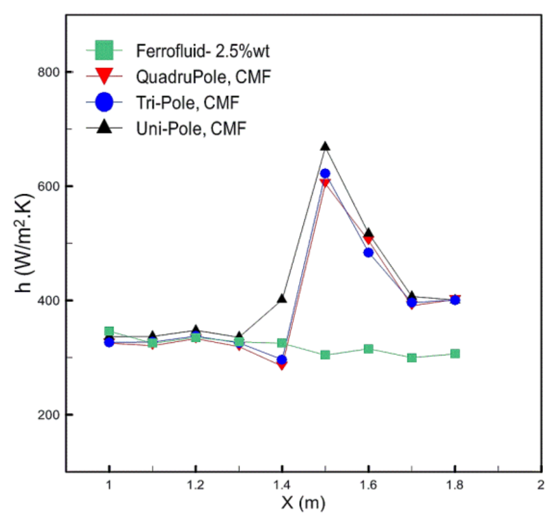


Fig. 8. Effect of different magnetic field configurations on the local heat transfer coefficient for ferrofluid with 2.5 % (wt) and at Re=2000.

C. *Heat transfer of ferrofluid in the presence of alternating magnetic field*

The effect of alternating magnetic field on the convective heat transfer was examined using the Uni-pole magnetic field system. The experiments are conducted using five different frequencies of (f = 2, 5, 10, 20, 40 HZ) at magnetic field intensity of 650 Gauss. Figure 9 shows the local convective heat transfer coefficient of ferrofluid with 2.5% mass concentration under alternating magnetic field with different frequencies at B = 650 G and Re = 2000. A maximum enhancement in heat transfer of 96.8% compared to the case without magnetic field was observed under alternating magnetic field at f = 2 HZ. As shown in Fig. 9, the convective heat transfer enhancement decreases as the alternating magnetic field frequency increases. It is worth mentioning that alternating magnetic field showed no enhancement in heat transfer for ferrofluid at higher frequencies. As mentioned earlier, the alternating magnetic field is generated by continuous connection and disconnection of the magnetic field. At the connection time, the magnetic force attracts the nanoparticles towards the electromagnets which start to align in the direction of tube surface forming short chains of nanoparticles. It takes no time for the nanoparticles to be released again with the flow when the magnetic field is disconnected. The continuous attraction and releasing of nanoparticles results in disturbance in the flow and better mixing which enhances the heat transfer under alternating magnetic field. This mechanism may be responsible for heat transfer enhancement in ferrofluid under alternating magnetic field. At higher frequencies, the connection and disconnection time is too short, so these effects aren't obvious which explains the disappearance of the heat transfer enhancement.

D. *Heat transfer of ferrofluid in the presence of rotating magnetic field*

The magnetic field system was also used to study the rotating magnetic field effect on the convective heat transfer. Different rotating speeds of (N = 60, 150, 300, 600, 1200 rpm) were investigated. In this section, the experiments were conducted using ferrofluid with 2.5% mass concentration at B = 650 G and Re = 2000. Figure 10 illustrates the effect of rotating magnetic field on the local heat transfer coefficient of ferrofluid at different rotating speeds. Results show 106.7% maximum enhancement in heat transfer for ferrofluid under rotating magnetic field at N = 60 rpm. Like the alternating magnetic field, the enhancement in heat transfer has decreased with the increase in the rotating magnetic field speed. Moreover, no enhancements in the heat transfer were observed at higher rotating speeds. As the rotating magnetic field turns on, the magnetic nanoparticles migrate towards the wall and start to rotate over the inner tube surface with the rotation of the magnetic field. The nanoparticles rotation over the inner surface creates turbulence in the ferrofluid flow and disturbs the thermal boundary layer which enhances heat transfer. At higher rotating speeds, the connection time for each electromagnet becomes too short for the nanoparticles to reach the surface so the enhancement disappears.

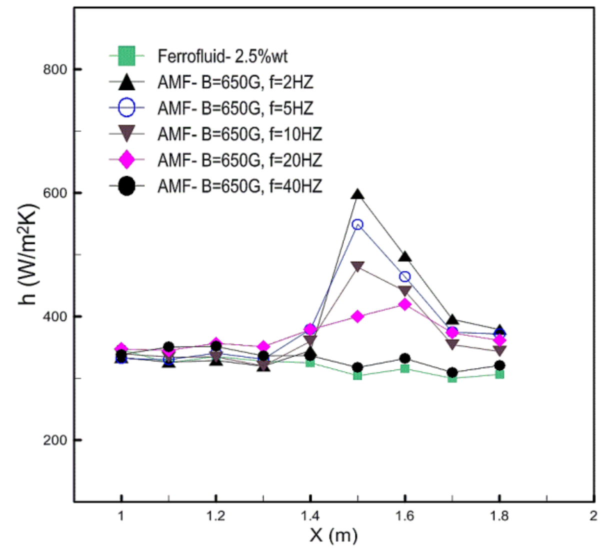


Fig. 9. Effect of alternating magnetic field (uni-pole) on local heat transfer coefficient at different frequencies for ferrofluid with 2.5% (wt) at B = 650 G and
Re = 2000.

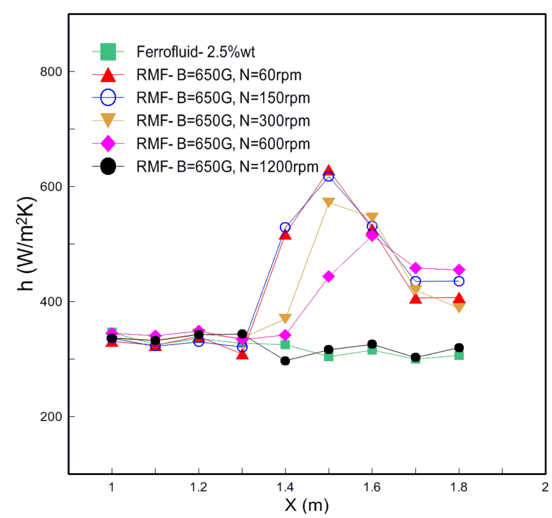


Fig. 10. Effect of rotating magnetic field (uni-pole) on local heat transfer coefficient at different rotating speeds for ferrofluid with 2.5% (wt) at B = 650 G and Re = 2000.

E. *Comparison between constant, alternating and rotating magnetic fields*

Figure 11 shows a comparison between the effect of constant, alternating (f = 2 HZ) and rotating (N = 60 rpm) magnetic fields on the heat transfer for ferrofluid with 2.5% mass concentration at B = 650 G and Re = 2000. As shown in Fig. 11, the constant magnetic field provides the maximum local enhancement then the rotating magnetic field and finally the alternating magnetic field. For instance, the constant magnetic field shows 119.6% as a maximum local enhancement in heat transfer compared to 106.7% and 96.8% for rotating magnetic field and alternating magnetic field, respectively. On the contrary, the rotating magnetic field enhancement is the predominant if the average heat transfer enhancement is considered instead of the maximum local enhancement. Results show 60.2% average heat transfer enhancement in the case of rotating magnetic field compared to 54.7% and 43.2% for constant magnetic field and alternating magnetic field, respectively. Consequently, the rotating magnetic field is considered to be the most efficient mode for heat transfer enhancement.

IV. CONCLUSION

This paper presents an experimental work on laminar convective heat transfer of ferrofluid in a copper tube under constant, alternating and rotating magnetic fields. For the magnetic field system, different operation modes were examined and the most efficient one was obtained. The effects of alternating magnetic field frequency and rotating magnetic

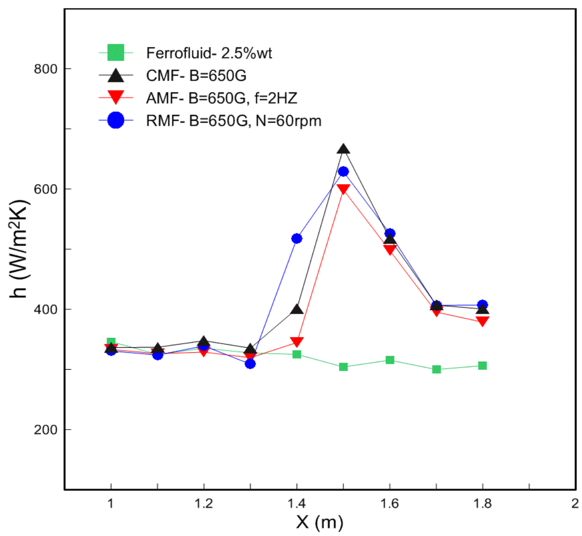


Fig. 11. Comparison between the effect of constant, alternating (f = 2 HZ) and rotating (N = 60 rpm) magnetic fields on the local heat transfer coefficient for ferrofluid with 2.5% (wt) at B = 650 G and Re = 2000.

field speed were investigated. The results can be concluded as follow.

- Application of a constant magnetic field enhances the convective heat transfer for ferrofluid.
- The magnetic field operation mode is an important parameter that affects the heat transfer enhancement. The Uni-pole system showed to be more efficient than the quadrupole and Tri-pole magnetic field systems.
- Using an alternating magnetic field leads to an increase in the convective heat transfer coefficient of ferrofluid. The heat transfer enhancement decreases by increasing the frequency of the alternating magnetic field.
- In the presence of a rotating magnetic field, the convective heat transfer showed to be increased for ferrofluid. Increasing the rotating magnetic field speed leads to a decrease in the heat transfer enhancement.
- The constant magnetic field provides the maximum heat transfer enhancement compared to the alternating and rotating magnetic fields. A maximum convective heat transfer enhancement of 119.6% is achieved by using a constant magnetic field for ferrofluid with 2.5% mass concentration at B = 650 G and Re = 2000. This value is decreased to 106.7% and 96.8% by application of rotating and alternating magnetic fields, respectively.

Nomenclature

A	tube surface area (m^2)
B	magnetic flux density (G)
C_p	specific heat (J/kg.K)
D_o	outside diameter of tube (m)
f	frequency (HZ)
h	convective heat transfer coefficient (W/m^2K)
I	electric current (A)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
N	rotating speed of magnetic field (rpm)
q''	heat flux (W/m^2)
Re	Reynolds number
T	Temperature (°C)
V	electric voltage (V)
x	axial distance from tube inlet (m)
x_*	a parameter in Eq. 10, = (x/D)/(Re Pr)
Z	evaluated variable in uncertainty analysis
Greek letters	
μ	dynamic viscosity (kg/m.s)
ρ	density (kg/m^3)
τ	connection plus disconnection time for alternating magnetic field (s)
τ_c	connection time for rotating magnetic field (s)
φ	volume fraction
Subscripts	
b	bulk
f	base fluid
ff	ferrofluid
i	inlet condition
o	outlet condition
p	particle
s	surface
Abbreviations	
AMF	Alternating magnetic field
CMF	Constant magnetic field
PVP	Polyvinylpyrrolidone (chemical substance)

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