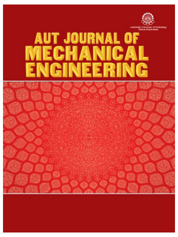

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Experimental investigation on laminar convective heat transfer of nano ferrofluids under constant and alternating magnetic field

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ABSTRACT: Due to unique characteristic behavior of ferrofluids, their rheological and thermophysical properties will be able to change in the external magnetic field. In this paper, the effects of constant and alternating magnetic field on the convective heat transfer coefficient of ferrofluids in a heated circular tube under laminar flow regimes ($200 \leq Re \leq 1600$) are investigated experimentally. The fluids considered in the experiment are distilled water and a Fe_3O_4/water nanofluid with 1% and 3% concentrations by weight (wt%). The obtained results are validated and a good agreement between the experimental data and predicted results is observed. In the absence of a magnetic field, the results illustrate the significant improvement of convective heat transfer for 3 wt% ferrofluid, compared to that of the distilled water as a working fluid. The heat transfer enhancement varies by changing the Reynolds number as well as ferrofluid concentration and the type of applied magnetic field. The results also show that with application of alternating magnetic field with frequency of 50 Hz, the maximum of 5% enhancement in the convective heat transfer coefficient is obtained compared to the case with no magnetic field.

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1- Introduction

Due to rapid advances in technology and consequently increasing heat flux density and operating temperature of the equipment, effective thermal management has become more serious and challenging especially in heat transfer engineering. Low heat transfer coefficient values of the conventional heat transfer fluids such as water, minerals oil and ethylene glycol cause serious concern in many fields of heat transfer systems [1]. In order to overcome these limitations, nanofluids as a new and promising working fluid have been introduced [2]. Nanoparticles are particles between 1 and 100 nanometers in size. Dispersion of nano-sized particles of different materials (metals, metal oxides, etc.) in a carrier fluid which is known as nanofluid. Nanofluids have been the subject of intensive investigations over the recent decades due to their potential applications in heat transfer and electronic cooling.

Investigation of nanofluids heat transfer has been studied considerably in the literature by all means of analytical solutions, experimental measurements, and numerical simulations [3, 4]. Numerous studies have been carried out on the performance of nanofluids' convective heat transfer both in laminar and turbulent flow regimes. Experimental work on the hydrodynamics and the heat transfer characteristics of nanofluids made of γ-Al_2O_3 nanoparticles and distilled water, flowing through a circular tube were performed by Esmaeilzadeh et al. [5]. The results showed considerable enhancement of the average heat transfer of nanofluid in comparison with distilled water as a working fluid. Zeinali Heris et al. [6] investigated laminar flow forced convection heat transfer of Al_2O_3-water nanofluid. They indicated that the heat transfer coefficient of nanofluids increases with Peclet number as well as nanoparticles concentration. Akhavan-Zanjani et al. [7] studied the convective heat transfer coefficient of Graphene-water nanofluid flowing through a uniformly heated circular pipe in laminar flow regime. They reported that low amounts of Graphene nanoparticles dispersed in water increases the thermal conductivity and the convective heat transfer coefficient of the working fluid. Chandrasekar et al. [8] presented an experimental study to evaluate the convective heat transfer and pressure drop characteristics of Al_2O_3-water nanofluid under laminar regime. They observed 12.24% increase in Nusselt number with a very low volume concentration of 0.1% at $Re = 2275$ compared to that of distilled water. No significant increase in pressure drop for the nanofluid in comparison with distilled water was observed.

Magnetic nanofluids are one kind of nanofluids consisting of superparamagnetic nanoparticles suspended in a nonmagnetic carrier fluid. These fluids are modern sets of nanofluids due to their unique characteristics behavior as smart or functional fluids. Their properties such as viscosity and conductivity can be changed under an external magnetic field, and their rheological characteristics can be accurately controlled. These properties and especially their capability of heat transfer enhancement make this kind of fluid an interesting issue for many researchers. Due to their unique characteristics,

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ferrofluids have been progressively employed in various applications in many engineering fields such as electronic, mechanical, aerospace and bioengineering.

Lajvardi et al. [9] experimentally investigated the convective heat transfer of a ferrofluid flowing through a heated copper tube in the laminar regime in the presence of a magnetic field. They investigated the strength of the magnetic field, the effect of magnetic nanoparticles concentrations, and the magnet position on the heat transfer of ferrofluid. Ghofrani et al. [10] presented an experimental investigation on forced convection heat transfer of an aqueous ferrofluid in the presence of an alternating magnetic field under a uniform heat flux and laminar flow conditions. They measured and compared the convective heat transfer coefficient for distilled water and ferrofluid under various conditions and investigated the effects of alternating magnetic field, volume concentration and the Reynolds number. Their results showed a maximum of 27.6% enhancement in the convection heat transfer. Azizian et al. [11] investigated the effect of an external magnetic field on the convective heat transfer and pressure drop of a ferrofluid under laminar flow regime conditions (Re < 830). They reported that the effect of the magnetic field on the pressure drop was not significant. The pressure drop increased only by up to 7.5% when a magnetic field intensity of 430 mT-was applied; however, the local heat transfer coefficient of the ferrofluid was increased up to 300%. Goharkhah et al. [12] experimentally studied the effects of constant and alternating magnetic field on the laminar forced convective heat transfer of Fe_3O_4/water in a heated tube and reported an increase up to 13.5% compared to the deionized water by using 2 vol% ferrofluid in the absence of a magnetic field. They also showed in the presence of 500 G intensity of magnetic field, this value grew up to 18.9% and 31.4% by application of constant and alternating magnetic field respectively. In another study [13] they have investigated the effect of an alternating magnetic field on the heat transfer and pressure drop of ferrofluid flow in a parallel plate channel. It was observed that in the absence of magnetic field, 16.4% enhancement was gained in the convective heat transfer at Re=1200 and 2 vol% of ferrofluid. Yarahmadi et al. [14] carried out an experimental study of applying both constant and alternating magnetic field on the forced convective heat transfer in a tube under laminar flow regime. They reported the maximum enhancement of 19.8% in the local convective heat transfer by using the oscillating magnetic field compared with the case of no magnetic field. Shahsavar et al. [15] achieved the maximum enhancement of 62.7% in the local Nusselt number for hybrid nanofluid containing 0.5 vol% Fe3O4 and 1.35 vol% CNT at Re=2190 compared to water as based fluid. They reported 20.5% enhancement in the local Nusselt number for hybrid nanofluid mentioned before at Re=548 due to the applied constant magnetic field. Hatami et al. [16] investigated experimentally the convection heat transfer of Fe_3O_4/water nanofluids through a uniformly heated circular tube in the laminar flow regime with and without an external magnetic field. They analyzed the effect of the external magnetic field, volume fraction of nanoparticles and flow rate on the heat transfer characteristics. Through the investigation, they reported that the laminar convective heat transfer increased more than 60% for 1 vol%. Esmaeili et al. [17] studied the effect of an external AC magnetic field on the convective heat transfer coefficients of magnetite nanofluids with different viscosities. Esmaeili et al. expressed that Neel and/or Brownian Mechanisms improved the heat generation resulted from the magnetic nanoparticles. The heat transfer behaviors of 3 vol% Fe_3O_4/water nanofluids in the presence of a parallel constant and uniform magnetic field were investigated experimentally in the uniformly heated circular tube by Sha et al. [18]. They measured and compared the convective heat transfer coefficient for distilled water and ferrofluid and also investigated the effects of temperature and magnetic field strength. In the absence of the magnetic field, an enhancement between 1.2% and 2.3% for laminar flow regime and between 4.7% and 5.6% for turbulent flow regime were observed compared to the cases with distilled water.

Applying an external magnetic field on the ferrofluids shows some differences in the results of the foregoing conducted researches. it has been reported in some researches that the application of a constant magnetic field enhanced the heat transfer of ferrofluids [11-13] while in some other investigations it has been observed that this kind of the magnetic field has no effect or even has an adverse effect on the heat transfer [10, 14, 16]. Moreover, there isn't an accurate understanding of the effect of alternating magnetic field on the heat transfer of ferrofluids and actually, it isn't illustrated clearly.

Research studies on the effects of external magnetic field on ferrofluids are rare in the literature and it is still not enough knowledge about the relationship between the heat transfer of the magnetic nanofluids and external magnetic field. Therefore, with respect to the contradictory statements, more efforts are necessary to gain an accurate insight into them.

In this paper, an experimental study is performed to investigate the effects of both constant and alternating magnetic field on the heat transfer of ferrofluid in laminar flow regime. The ferrofluid considered is Fe_3O_4/water nanofluid which is circulated in horizontal heated tube. The effects of the frequency of the alternating magnetic field and concentration of nanoparticles as well as a wide range of flow rate are examined in this investigation. The results are validated with reliable equations such as Shah [19] and extensive experiments are performed to measure various parameters for the cases considered.

2- Experimental setup

An experimental setup was built to study the effect of the constant and alternating external magnetic field on the forced convective heat transfer of Fe_3O_4/water nanofluids in a horizontal heated tube. The schematic diagram and photograph of the experimental setup are presented in Figs. 1 and 2, respectively. The experimental setup consists of three main sections: the tube test section with other equipment to circulate the working fluid and acquire temperature values, magnetic field generation with other electrical instrumentations and, finally, the preparation of ferrofluid.

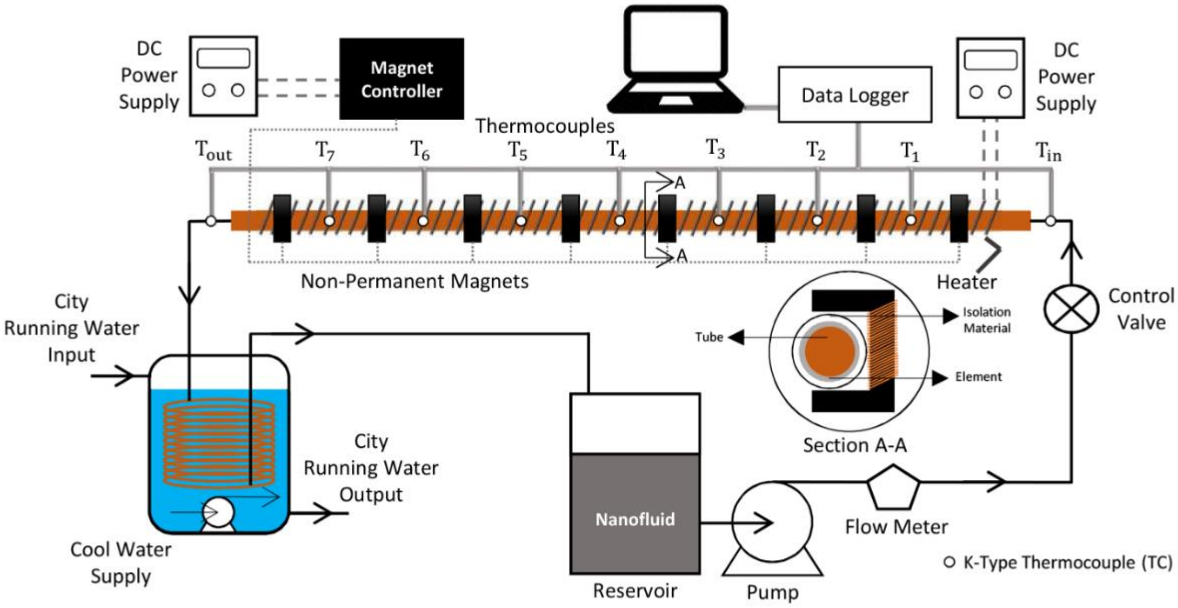


Fig. 1. A schematic diagram of the experimental setup.

Fig. 2. The experimental setup photograph

2- 1- Apparatus

The experimental setup consists of a heating and cooling unit, circulation part equipped with two pumps, thermocouples and measuring system. The main part of the test section was fabricated from smooth straight copper tube with 700mm length, and the inner and outer diameters of 9.5mm and 10mm, respectively. It is worthwhile to mention that to ensure the existence of fully developed laminar flow at the test section (700mm length) for different Reynolds numbers, the length of entrance region has been calculated and considered in the construction of experimental setup. For laminar flow inside the pipe, this length is a function of the Reynolds number. To apply a constant-heat flux on the outer surface of the tube, a nickel–chromium heating element with a resistance of 25 Ω/m and a diameter of 0.15mm was utilized. A DC power supply with a maximum output of 150W provided the power of this element. In order to prevent producing magnetic field by the electric current which passes through the element, it wrapped around the tube mutually. The whole test section was well insulated with elastomeric foam to minimize heat loss. All of the experiments were carried out in indoor condition with ambient temperature of 25 ◦C. With a sufficient thickness of insulation, a maximum of 9 % of heat loss was measured. The working fluid was stored in a reservoir with capacity of 3l connected to a pump with 110W power, in order to circulate the fluid through the test section. To have a closed flow cycle for the working fluid a cooling unit was used to cool down the working fluid after being heated in the test section. The cooling unit consists of a spiral copper tube immersed in a cooling water bath. Moreover, a pump with 20W power was used to circulate water in the cooling bath in order to maintain the temperature of the bath constant. Therefore, the inlet temperature of the working fluid remains constant and the steady-state circulation can be achieved. A calibrated rotameter was used to adjust the volumetric flow rate. 9 calibrated K-type thermocouples were used to measure the outer surface of tube wall and the bulk fluid temperature. Two thermocouples were installed inside the tube at the inlet and outlet of the tube test section to measure the flow temperature more accurately. In order to measure the local wall temperature, seven other thermocouples were attached at different places of the tube surface with a distance of 75mm from each other. A 4-channels data acquisition system (Lutron TM-946) was employed to record the temperature values. For all Reynolds numbers reported in this study, the difference between the applied constant heat flux on the outer surface of the tube and the amount of heat transferred to the working fluid was calculated. In this regard, with a sufficient thickness of insulation, a maximum of 9 % of heat loss was measured. The connections between the parts were established with pneumatic connectors and fittings due to the low pressure of the system considered in this study.

2- 2- Electrical instrumentation and control system

In this experiment, a circuit with a programmable microcontroller especially designed to control the current of the electromagnets was employed. The strength of both constant and alternating magnetic fields was controlled by the circuit. Moreover, the connection or the disconnection time of pulse waves which are known as duty cycle was adjusted by the microcontroller programming of this circuit as well as the frequency of the alternating magnetic field. The circuit had also the ability to manage how the electromagnets are turned on or off. This circuit was one of the main sections of the setup which generates various pulse waves with specific frequency and duty cycle for an alternating magnetic field. To produce an accurate alternating magnetic field, it is essential to use non-permanent magnets made of low hysteresis and a high saturation flux density. Hence to generate an appropriate alternating and constant magnetic field, eight non-permanent magnets consist of U-shaped zinc ferrite powder were used. Dimension and arrangement of the cores are shown in Fig. 3. The copper tube was placed between the empty space of the magnets and the eight magnets were located at the same distance from each other along the tube. With 2000 rounds of copper wire no. 20 wrapped around the U cores, it was achievable to apply 300 G in the inside fluid flowing through the tube. This selected magnetic field strength is an acceptable value for investigating the effects of the magnetic field on nanoparticles while not having the opposite effect of their deposition. The other electrical structure of the system includes a DC power supply (RN3005S, Iran) and a digital multimeter (VC9805, China). DC power supply with 150W power used to provide required current density in all the windings of U cores and digital multimeter act as measuring unit of voltage or current of element etc. Moreover, an accurate Tesla meter (Lutron MG-3002) was used to measure the magnetic field magnitude.

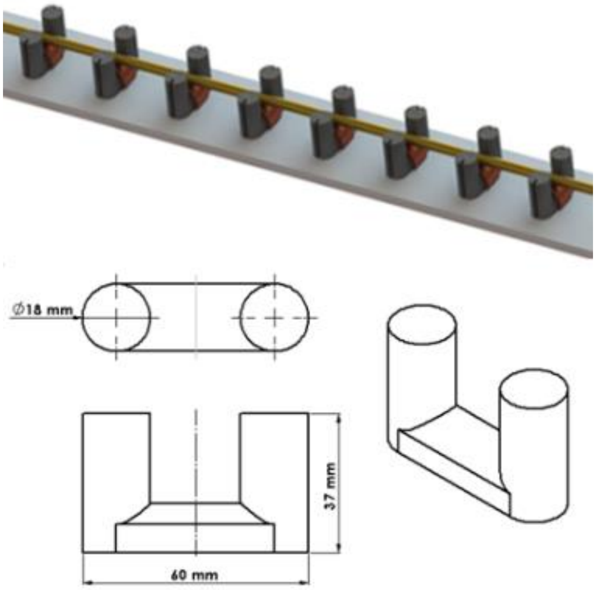


Fig. 3. Dimension and arrangement of the cores

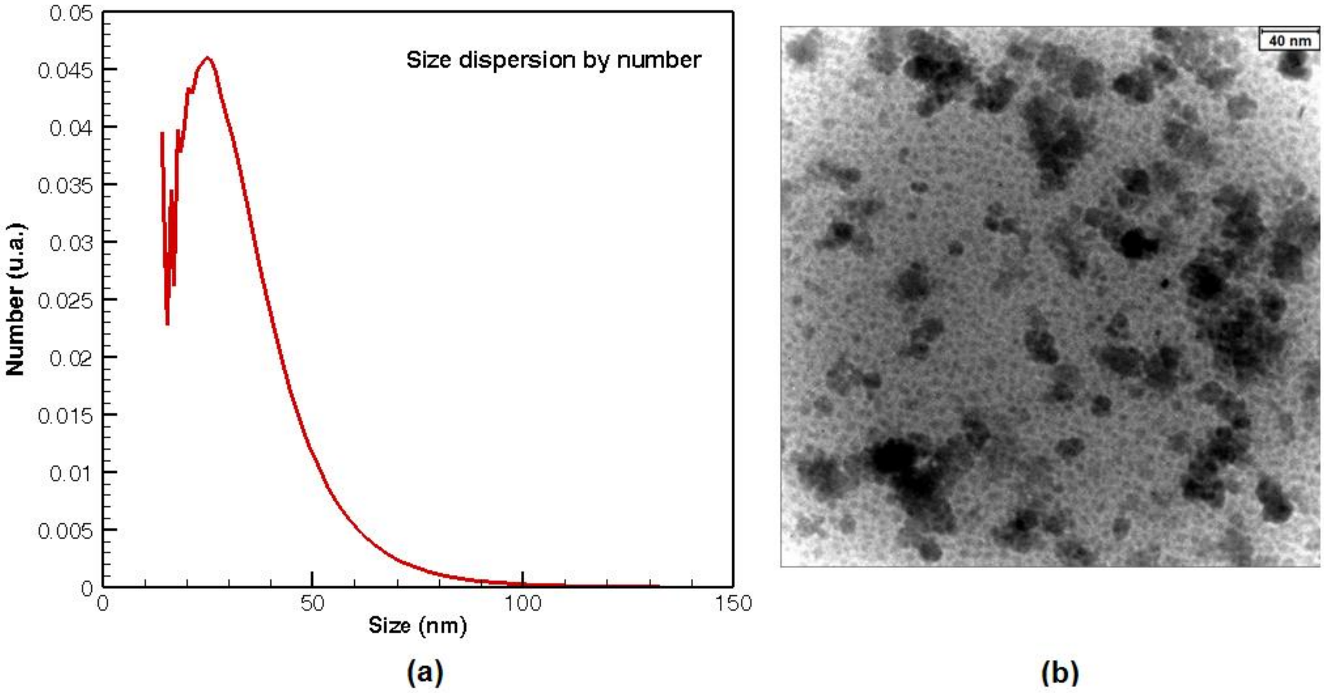
2- 3- Ferrofluid characterization and properties

Ferrofluids are mainly consisted of magnetic nano-particles of metal oxide such as Fe_3O_4, γ- Fe_2O_3 and spinel-type ferrites of MFe_2O_4 (with M=Mn, Co, Zn, Ni, etc.) because of their chemical stability [1]. Various methods such as chemical co-precipitation, micro-emulsion and phase transfer are used to produce these particles [1, 2]. In this research, the sample magnetite nanoparticles were synthesized by the chemical precipitation method [3, 4]. The procedure is explained as follows. First of all the dissolved oxygen of 200ml of DI-water was eliminated by bubbling nitrogen gas (N_2) for 15 min continuously to prevent the solution from the reactions with oxygen (O_2). Next a solution of 5.12g ferric chloride hexahydrate ($FeCl_3.H_2O$) and 2.00g of ferrous sulfate ($FeSO_4$) were dissolved in DI-water. Subsequently, the mixture heated slowly to 80°C under mechanical stirring (with a 600 rpm). Then ammonium hydroxide (NH_4OH with 1.5 M) under nitrogen atmosphere and vigorous stirring gradually added drop wise into the solution. As the pH reaches 8, the solution turns black which indicate the precipitation of iron oxide nanoparticles. The solution was allowed to maintain under the stirring rate, temperature and nitrogen bubbling conditions for 2 h. Finally, the synthesized black Fe_3O_4 nanoparticles was removed from unwanted solution of NH_4OH via magnetic separation. The nanoparticles were then washed several times by deionized water to reach a neutral pH and dried in the air atmosphere [5]. The obtained solid Fe_3O_4 powder in appropriate amount was weighed by an electronic scale accurate to 0.001 g and with a desired volume concentration dispersed in distilled water. In this study, in order to prepare a stable suspension, acetic acid ($C_2H_4O_2$) was used. Therefore, the proper volume fraction of acetic acid was added to the suspension and the ferrofluid placed under the intensive ultrasonic mixing for 30min. It was observed that with this method, the stability of prepared magnetic nanofluid remarkably improved not only in the case of no magnetic field (for at least a month) but also in the case of applied magnetic field. Size dispersion by the number of the synthesized Fe_3O_4 nano particles and transmission electron microscopy (TEM) are shown in Fig. 4 (a) and (b), respectively. As seen in the figures, the mean diameter of the magnetite nanoparticles are 30 nm.

The thermophysical properties of the prepared nanofluids are calculated using the following equations [25]:

$$\rho_{nf} = \phi.\rho_p + (1-\phi).\rho_f \tag{1}$$

$$C_{\rho,nf} = \frac{\phi.(\rho_p.C_{p,p}) + (1-\phi).(\rho_f.C_{p,f})}{\rho_{nf}} \tag{2}$$



(a)

(b)

Fig. 4. Size dispersion by the number of the synthesized Fe3O4 nano particles (a) and transmission electron microscopy (TEM) (b).

where ρ, p, f and nf are density, nanoparticles, fluid, and nanofluid, respectively. The volume fraction ratio of nanoparticles in a suspension solution of the base fluid (ϕ) can be calculated as

$$\phi = \frac{m_p / \rho_p}{m_p / \rho_p + m_f / \rho_f} \tag{3}$$

where m_p and m_f are the mass of the nanoparticles and the fluid, respectively.

The viscosity of the nanofluid is estimated using the Einstein equation [26]. This equation is applicable for the suspensions of low particle concentrations (lower than 2 vol. %), where particle-particle interactions are negligible:

$$\mu_{nf} = \mu_f (1 + 2.5\phi) \tag{4}$$

where μ_{nf} and μ_f is the viscosity of nanofluid and fluid, respectively. Term ϕ is the nanoparticles volume fraction which is explained in Eq. (3). All the properties are measured at the mean temperature of Fe_3O_4/water nanofluids.

3- Data analysis

In this study the local convective heat transfer coefficient is utilized in order to estimate the heat transfer enhancement as follows:

$$h(x) = \frac{q''}{T_w(x) - T_{nf}(x)} \tag{5}$$

where q'' is the constant heat flux applied to the copper tube, T_w (x) is the tube wall temperature measured by thermocouples and T_{nf} (x) is the nanofluid temperature at x axial distance from the inlet of the tube which can be calculated by the energy analysis as:

$$T_{nf}(x) = \frac{qx}{L\dot{m}C_{p,nf}} + T_{nf,i} \tag{6}$$

where ṁ is the mass flow rate, L is the tube length. Terms $C_{p,nf}$ and $T_{nf,i}$ are the specific heat and the inlet temperature of nanofluid, respectively.

In Eq. (6), q represents the heat flow which also can be used to calculate the constant heat flux applied to the copper tube in Eq. (5), by:

$$q'' = \frac{q}{A} = \frac{VI}{\pi DL} \tag{7}$$

where V is the voltage and I is the current which are used by the element and kept constant during the experiment. A and D are the surface area and the inner diameter of tube, respectively.

The average value of the convective heat transfer coefficient is obtained by:

$$h_{ave} = \frac{1}{L}\int_0^L h(x)dx \tag{8}$$

Finally, to evaluate and compare the applied cases with each other, the enhancement percentage in the heat transfer is presented as follows:

$$\eta = \frac{h_{nanofluid} - h_{water}}{h_{water}} \times 100 \tag{9}$$

4- Apparatus validation

In order to investigate the reliability and accuracy of the experimental apparatus, Shah-equation, which calculates the theoretical local Nusselt number for laminar flow under the constant heat flux boundary condition, has been used as follows [19]:

$$Nu = \begin{cases} 0.0722\left(\mathrm{Re}\,\mathrm{Pr}\dfrac{D}{x}\right) + 4.364, & \mathrm{Re}\,\mathrm{Pr}\dfrac{D}{x} < 33.3 \\ 1.953\left(\mathrm{Re}\,\mathrm{Pr}\dfrac{D}{x}\right)^{\frac{1}{3}}, & \mathrm{Re}\mathrm{Pr}\dfrac{D}{x} \geq 33.3 \end{cases} \tag{10}$$

where x is axial distance from the inlet of the tube, D is the tube internal diameter, Re is the Reynolds number $\left(\frac{\rho VD}{\mu}\right)$, and Pr is the Prandtl number $\left(\frac{c_p \mu}{k}\right)$.

A series of experiments with distilled water as the working fluid were conducted for some different Reynolds numbers in the laminar flow regime (200≤Re≤1600). Then the collected data for each specific Reynolds numbers were compared with the results estimated from Shah equation (Eq. (10)). The results of this investigation indicated a good agreement between the Shah equation and the measurements. Fig. 5 shows two different Reynolds numbers of this investigation as sample. As it can be seen, there is a good agreement between the Shah equation and the measurements.

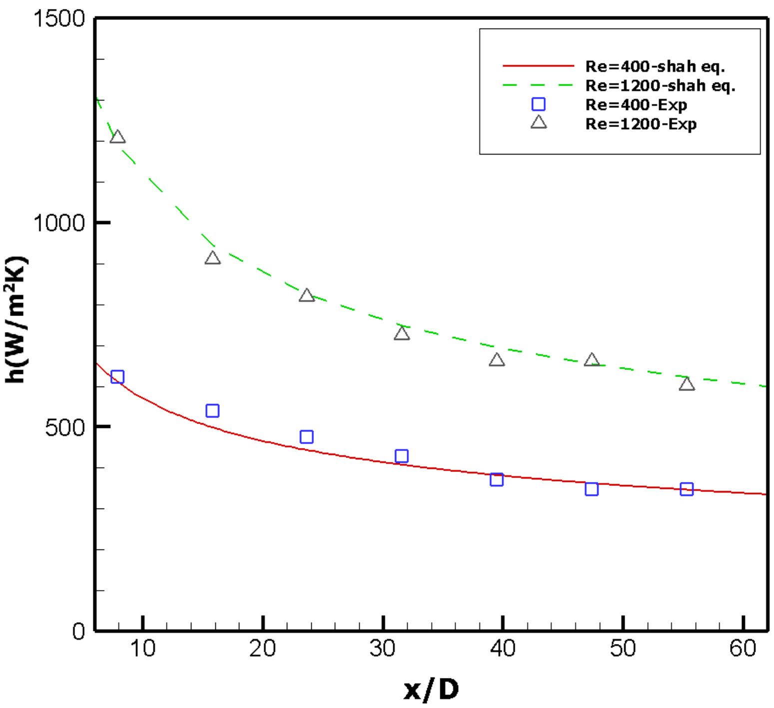


Fig. 5. Validation of the experimental setup with Shah equation along dimensionless distance from the tube entrance using distilled water.

5- Uncertainty analysis

Evaluation of errors in the experiments is necessary to perform a valid test. For a parameter, ν, the total uncertainty (δν) can be calculated as follows:

$$\delta v = \sqrt{\left(\delta v_{rep}\right)^2 + \left(\delta v_{eqp}\right)^2} \tag{11}$$

where δv_{rep} and δv_{eqp} are the repetition and the equipment uncertainty, respectively. It should be mentioned that in this investigation, all measurements were taken three times to minimize the measurement error.

If R is a function of 'n' independent linear parameters as $R=R(v_1,v_2,\ldots,v_n)$, in order to estimate the uncertainty of function R the following equation is used:

$$\delta R = \sqrt{\left(\frac{\partial R}{\partial v_1}\delta v_1\right)^2 + \left(\frac{\partial R}{\partial v_2}\delta v_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial v_n}\delta v_n\right)^2} \tag{12}$$

where δR is the uncertainty of function R, δv_i the uncertainty of parameter v_i, and $\partial R/\partial v_i$ is the partial derivative of R with respect to parameter v_i. If the uncertainty in $v_1,v_2,\ldots,v_m,v_{m+1},\ldots,v_n$ are independent, then the fractional uncertainty of R is written as [27]:

$$\frac{\delta R}{R} = \sqrt{\left(\frac{\delta v_1}{v_1}\right)^2 + \left(\frac{\delta v_2}{v_2}\right)^2 + \cdots + \left(\frac{\delta v_m}{v_m}\right)^2 + \left(-\frac{\delta v_{m+1}}{v_{m+1}}\right)^2 + \cdots + \left(-\frac{\delta v_n}{v_n}\right)^2} \tag{13}$$

As an example, the local convection heat transfer coefficient (h) is a function of several parameters ($f(V,I,D,L,T_s,T_m)$ see Eq. (5)); therefore, the uncertainty of h (considering the maximum uncertainties for each of the parameters) can be calculated as:

$$\delta h = \sqrt{\left(\frac{\partial h}{\partial V}\delta V\right)^2 + \left(\frac{\partial h}{\partial I}\delta I\right)^2 + \left(\frac{\partial h}{\partial D}\delta D\right)^2 + \left(\frac{\partial h}{\partial L}\delta L\right)^2 + \left(\frac{\partial h}{\partial T_s}\delta T_s\right)^2 + \left(\frac{\partial h}{\partial T_m}\delta T_m\right)^2} \tag{14}$$

by substituting the terms of the Eq. (14) from Eq. (5) and simplifying, the fractional uncertainty of h is presented as follows:

$$\frac{\delta h}{h}=\sqrt{\left(\frac{\delta V}{V}\right)^2+\left(\frac{\delta I}{I}\right)^2+\left(\frac{\delta D}{D}\right)^2+\left(\frac{\delta L}{L}\right)^2+\left(\frac{\delta T_s}{T_s-T_m}\right)^2+\left(\frac{\delta T_m}{T_s-T_m}\right)^2} \tag{15}$$

The uncertainties associated with the measuring instruments of the experimental setup are reported in Table 1. For all measurements, uncertainty values have been calculated and the average uncertainty for local convection heat transfer coefficient and injected power were equal to ±3.4 % and ±0.65 %, respectively.

6- Results and Discussion

In this investigation, various sets of experiments were carried out to analyze the convective heat transfer features of ferrofluid in the absence or presence of two types of magnetic field. In order to prevent any undesirable uncertainty from calculating thermal conductivities of ferrofluids, Nusselt numbers were not presented in this study. All measurements were taken three times to minimize the measurement error. It should be mentioned that the performance of the system was recorded in steady-state condition.

6- 1- Convective heat transfer performance of ferrofluid in the absence of magnetic field

Two working fluids were employed in this study: distilled water and a Fe3O4/water nanofluid with two different volume concentrations (1 wt%, 3 wt%). a series of experiments were performed for five different Reynolds numbers in the laminar flow regime (200≤Re≤1600). The variations of the local heat transfer coefficient against the dimensionless distance from the tube entrance (x/D) at Re = 400 are shown in Figs. 6 (a) and (b), respectively.

As Fig. 6 shows, the local convective heat transfer coefficient (h) reduces till the flow approaches fully developed laminar region. As it can be seen, the local convective heat transfer coefficient (h) at short axial distances from the test tube entrance is relatively more than the larger distances which demonstrates the significance of the thermal boundary layer disturbance in the heat transfer enhancement process. In Fig. 7, the average convective heat transfer coefficient of 3 wt% ferrofluid in comparison with 1 wt% ferrofluid and distilled water for different Reynolds numbers are shown. The comparison of Figs. 6 and 7 shows that adding Ferro nanoparticles to water by 1 wt% under no magnetic field, have negligible effect (around 1%) on the local convective heat transfer coefficient. It is also revealed that by tripling the ferrofluid concentration from 1 wt% to 3 wt%, about 5.5% improvement in the average convective heat transfer coefficient is observed. As experimental observations show, the convective heat transfer coefficient of the system for 1 wt% magnetic nano particles is slightly more than the case when the working fluid is distilled water. Particle migration, nanoparticle clustering, viscosity gradient and Brownian motion are a number of mechanisms discerned as the probable reasons for heat transfer enhancement in nanofluids [9, 20, 28-30]. The disturbed thermal boundary layer due to the addition of nano particles along with the increase of the thermal conductivity of the nanofluid are among other reasons for the enhancement of the convective heat transfer coefficient.

6- 2- Convective heat transfer performance of ferrofluid in the presence of magnetic field

The quality of an alternating magnetic field is specified with the two most important features of it which are known as frequency and duty cycle (the connection or the disconnection time of pulse waves). In this study, the alternating magnetic field of 10 Hz and 50 Hz was applied to the test section. The duty cycle of two kind of magnetic fields are equal. The strength of constant magnetic field is 300 Gauss, it should be mentioned that all kinds of alternating magnetic field have the same strength. In the presence of magnetic field the results are presented and compared for four different cases: the results of ferrofluid with no magnetic field, ferrofluid with a constant magnetic field, ferrofluid with an alternating magnetic field of 10 Hz and 50 Hz with the same strength. For the purpose of studying the effect of 1 and 3 wt% ferrofluid on the local heat transfer coefficient, two Reynolds numbers have been selected in the figures. In Fig. 8, the local heat transfer coefficient of 1 wt% ferrofluid against the dimensionless distance from the tube entrance (x/D) at Re = 1200 for all cases is shown. As seen in Fig. 8, applying an alternating magnetic field with a frequency of 50 Hz and 10 Hz increases the local

Table 1. Equipment and their accuracy

Equipment and model	Measurement section	Accuracy
caliper	Diameter	±0.02 mm
Measuring tape	length	±1 mm
K type thermocouple	Wall and Fluid temperature	±0.15 °C to ±0.25 °C
Digital multimeter	Voltage	±(0.5 + 1) V
	current	±(0.5 + 1) A

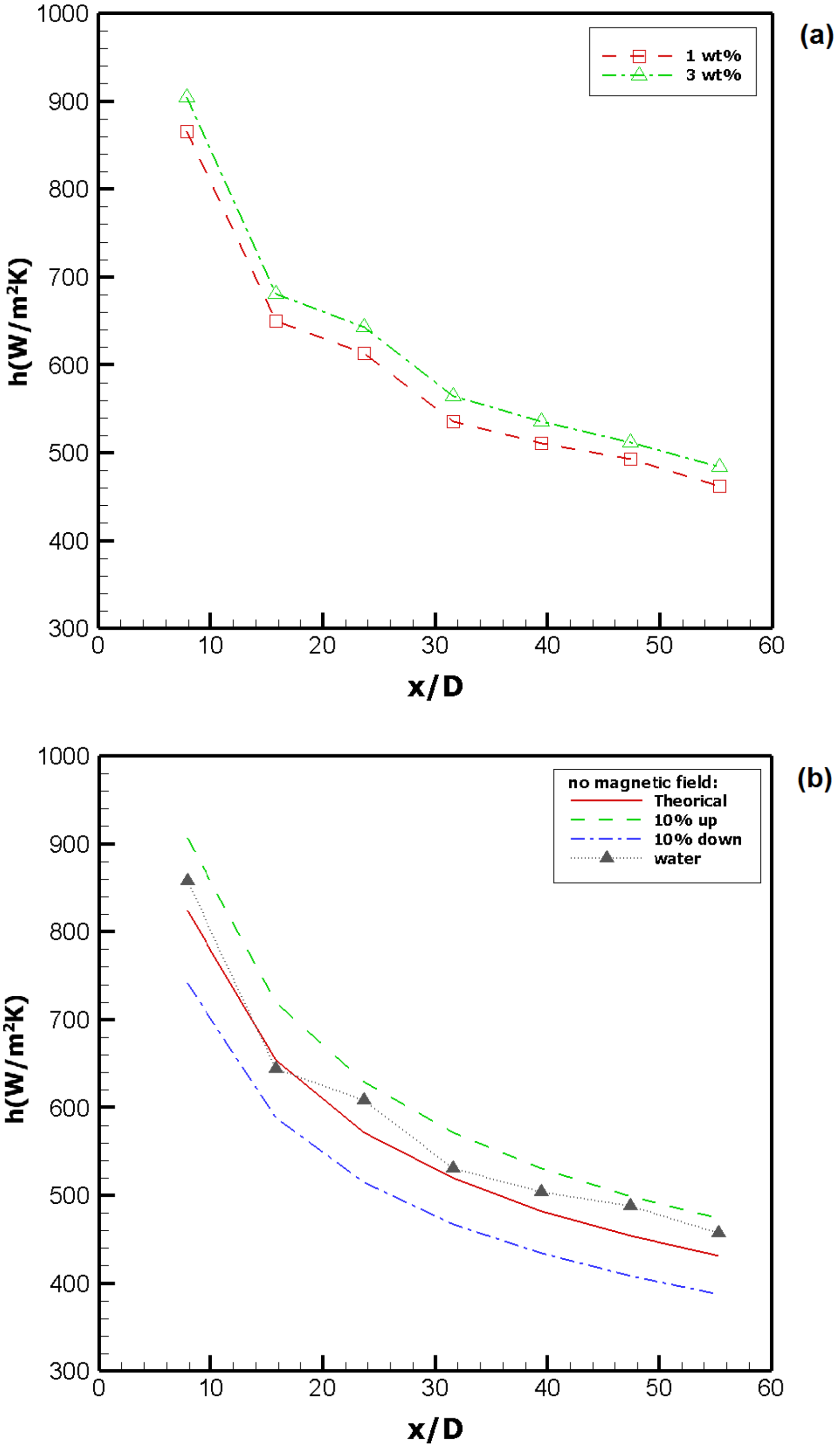


Fig. 6. the local heat transfer coefficient against the dimensionless distance from the tube entrance (x/D) at Re = 400 for ferrofluid (a) and distilled water versus Shah-equation (Theoretical) (b).

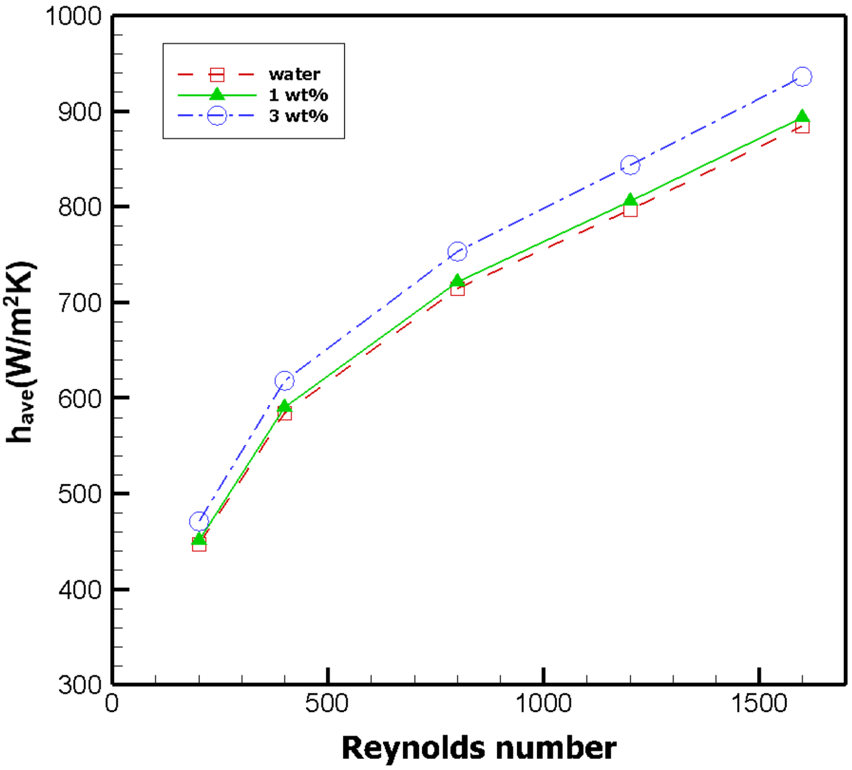
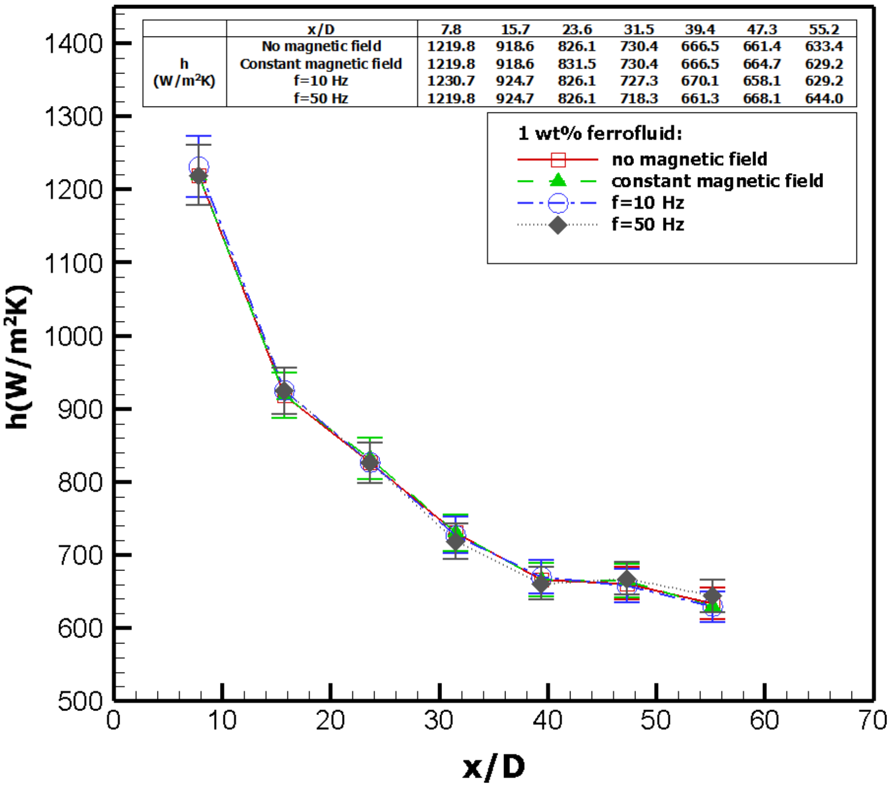
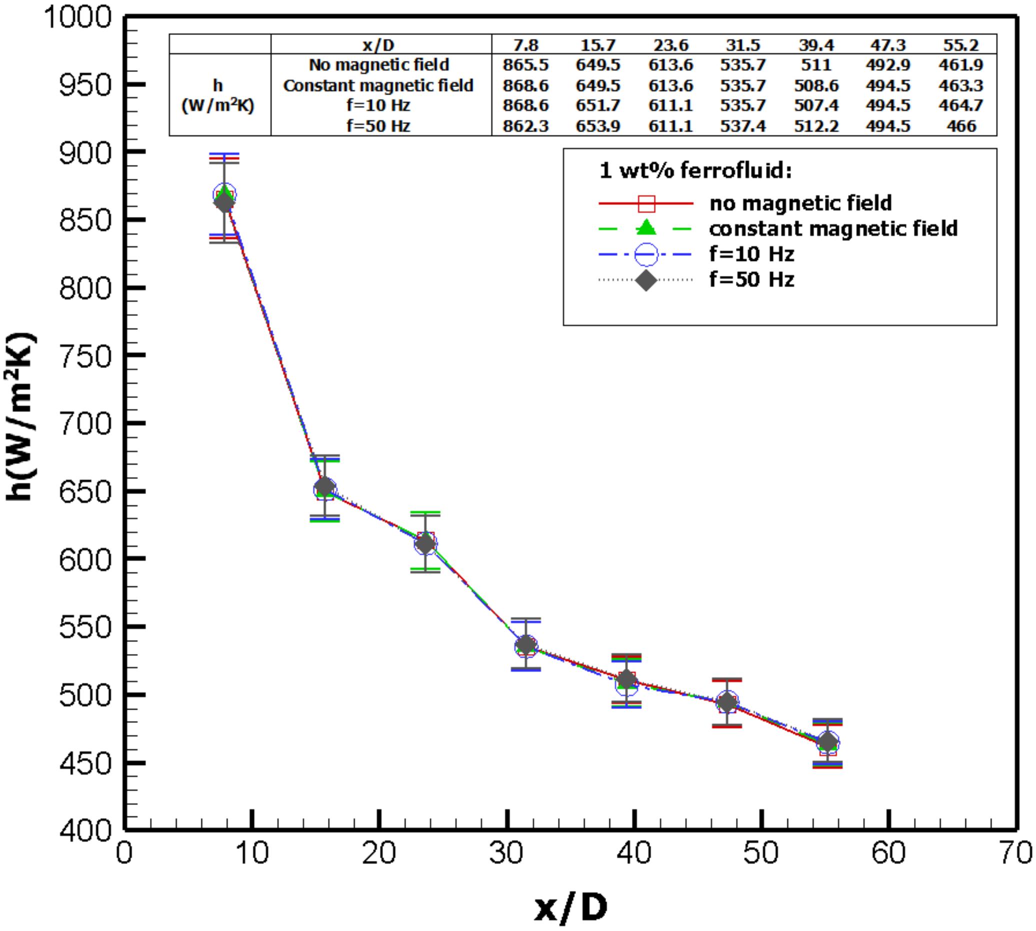


Fig. 7. The average convective heat transfer coefficient of 3 wt% ferrofluid in comparison with 1 wt% ferrofluid and distilled water for different Re.



	x/D	7.8	15.7	23.6	31.5	39.4	47.3	55.2
h (W/m^{2}K)	No magnetic field	1219.8	918.6	826.1	730.4	666.5	661.4	633.4
	Constant magnetic field	1219.8	918.6	831.5	730.4	666.5	664.7	629.2
	f=10 Hz	1230.7	924.7	826.1	727.3	670.1	658.1	629.2
	f=50 Hz	1219.8	924.7	826.1	718.3	661.3	668.1	644.0

Fig. 8. The local heat transfer coefficient of 1 wt% ferrofluid against the dimensionless distance from the tube entrance (x/D) at Re = 1200 for all cases.



	x/D	7.8	15.7	23.6	31.5	39.4	47.3	55.2
h (W/m²K)	No magnetic field	865.5	649.5	613.6	535.7	511	492.9	461.9
	Constant magnetic field	868.6	649.5	613.6	535.7	508.6	494.5	463.3
	f=10 Hz	868.6	651.7	611.1	535.7	507.4	494.5	464.7
	f=50 Hz	862.3	653.9	611.1	537.4	512.2	494.5	466

Fig. 9. The local heat transfer coefficient of 1 wt% ferrofluid against the dimensionless distance from the tube entrance (x/D) at Re = 400 for all cases.

heat transfer coefficient of 1 wt% ferrofluid in comparison to the case with no magnetic field. However, this value is not as much as be noticeable. It is also observed that the local heat transfer coefficient of 1 wt% ferrofluid for a constant magnetic field is very close to that of the system when no magnetic field is applied.

Fig. 9 also shows the local heat transfer coefficient of 1 wt% ferrofluid for the same cases and conditions as of Fig. 8 except for the Reynolds number which is 400 in Fig. 9.

Similar to the obtained results for Re=1200, applying an alternating magnetic field slightly improves the local heat transfer coefficient of system for Re=400. The enhancement percentage in the heat transfer of 1 wt% ferrofluid under constant and alternating magnetic fields is presented in Fig. 10. It is seen that the results of using 1 wt% ferrofluid without any kind of magnetic field are close to the case in which distilled water is the working fluid. In this case, about 1% improvement in comparison with using distilled water is observed. Fig. 10 also reveals that applying constant or alternating magnetic field, has no considerable effect on the heat transfer enhancement with ferrofluid as the working fluid.

Another working fluid employed in this study was 3 wt% ferrofluid concentration. In Fig. 11 the effect of the constant and alternating magnetic fields on the local heat transfer coefficient of 3 wt% ferrofluid along the axial distance (x/D) at Re = 1600 is displayed. As Fig. 11 shows, the local heat transfer coefficient at short distance from the tube entrance is slightly more than longer distances and keeps constant to the end of it.

The local heat transfer coefficient for the 3 wt% ferrofluid for the same cases as of Fig. 11 but for a lower Reynolds number (Re=400) is presented in Fig. 12.

The average convective heat transfer coefficient of 3 wt% ferrofluid under the constant and alternating magnetic field in comparison with no magnetic field for Reynolds number is illustrated in Fig. 13. As seen from the figure, using an alternating magnetic field increases the convective heat transfer of ferrofluid and in comparison with 1 wt% ferrofluid the effect of an alternating magnetic field is more than the constant magnetic field.

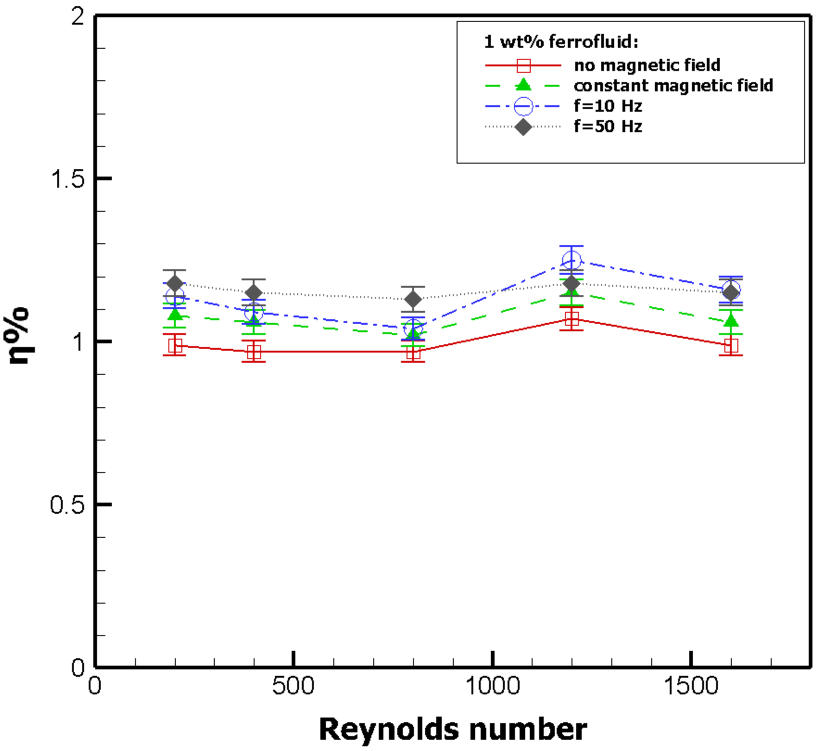


Fig. 10. The enhancement percentage in the heat transfer of 1 wt% ferrofluid under the effect of constant and alternating magnetic field.

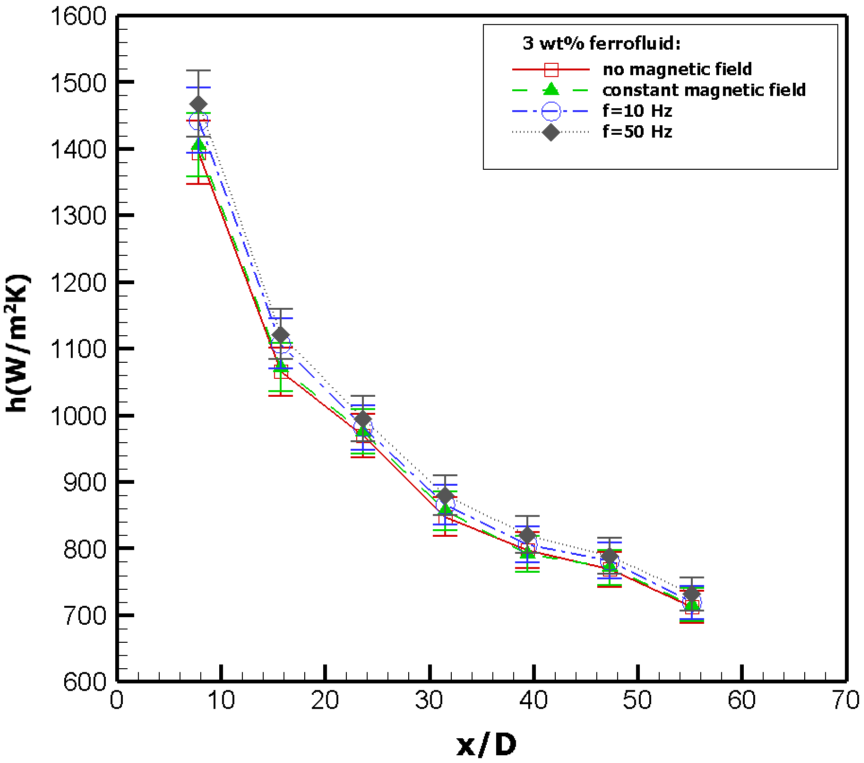


Fig. 11. the effect of the constant and alternating magnetic field on the local heat transfer coefficient of 3 wt% ferrofluid along the axial distance (x/D) at Re = 1600.

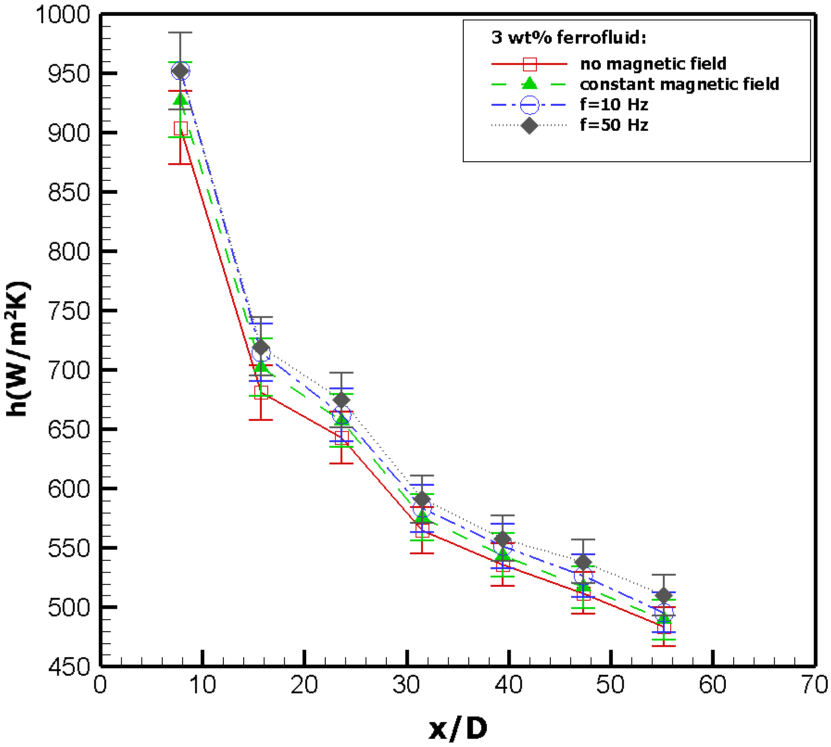


Fig. 12. the effect of the constant and alternating magnetic field on the local heat transfer coefficient of 3 wt% ferrofluid along the axial distance (x/D) at Re = 400.

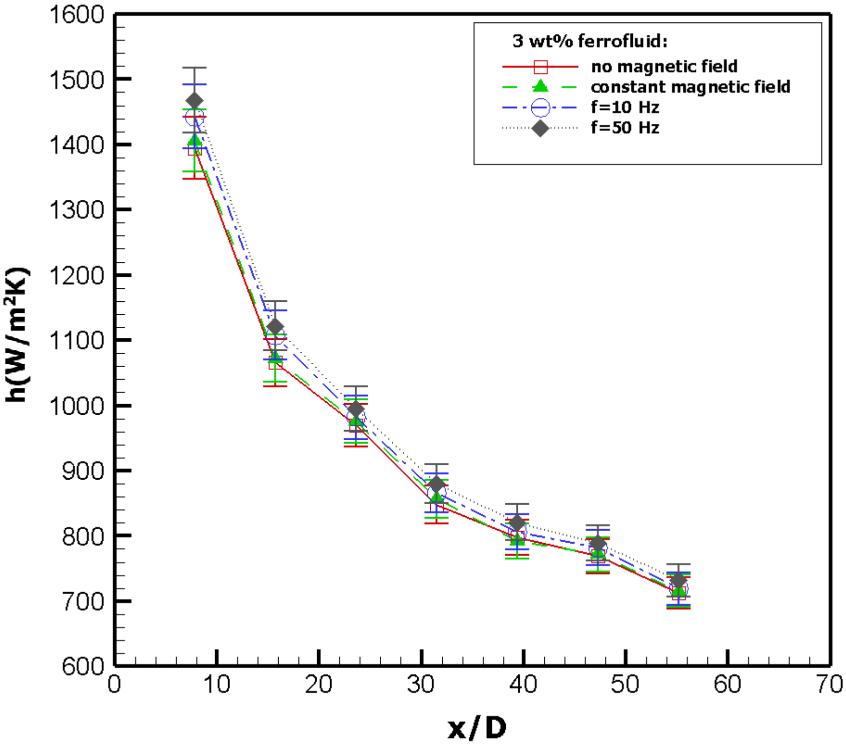


Fig. 13. The average convective heat transfer coefficient of 3 wt% ferrofluid under the effect of constant and alternating magnetic field in comparison with no magnetic field.

With respect to Fig. 11, Fig. 12 and Fig. 13, there is a considerable point about the relationship between the application of an external magnetic field and the Reynolds number. As the results reveal, as much as the Reynolds number is decreased the effect of magnetic field, whether constant or alternating, becomes more efficient. For instance, the amount of the convective heat transfer of 3 wt% ferrofluid for an alternating magnetic field of 50 Hz at Re=1600 is about 972 and is 936 when no magnetic field applied (an increase of 3.8%). But by reducing the Reynolds number from 1600 to 400, the amount of convective heat transfer is slightly higher and ranges from 617 to 649 (an increase of 5%) for the case with no magnetic field and alternating magnetic field of 50 Hz, respectively. This occurrence can be inferred from the relation between hydrodynamic force and the motion induced by a magnetic field on a particle which is known as magnetophoresis [31]. In this regard, when the Reynolds number increases, more nanoparticles pass through the tube section, but in this case, the magnetic field will be less effective. Hence, decreasing the Reynolds number also leads to the decrease in hydrodynamic force and in consequence, the magnetic field is more capable to absorb nanoparticles toward the tube's wall. As a result, in the same magnetic field strength as much as the flow rate decreases, the effect of magnetic field on the absorption of nanoparticles increases. Fig. 14 shows the effect of constant and alternating magnetic field on the heat transfer improvement of 3 wt% ferrofluid. As can be seen from Fig. 14, the enhancement percentage in the heat transfer for 3 wt% ferrofluid with no magnetic field is enhanced about 5% compared to distilled water for all Reynolds numbers. The enhancement percentage with applying the alternating magnetic field with a frequency of 50 Hz, 10 Hz and constant magnetic field reach the value of 5%, 3.7% and 2% for Re=400, respectively. It is also observed that by increasing the Reynolds number, the heat transfer enhancement decreases which is explained before. Therefore, it can be concluded that the enhancement percentage in the heat transfer of 3 wt% ferrofluid by means of an alternating magnetic field with a frequency of 50 Hz increases by about 3-5 % in comparison to the case with no magnetic field.

The difference between the results for the two kinds of applied magnetic field is worth mentioning. As explained, the constant magnetic field is seen to have a considerable effect on the heat transfer improvement when the flow rate decreases enough. With applying alternating magnetic field, however, the heat transfer is improved. This phenomenon may be explained by ferro particle distribution and their cluster morphology. The presence of these particle clusters and their chained alignment due to the external magnetic field as well as disturbing thermal boundary layer translates into more heat transfer in this case. Further details regarding the physical justification of heat transfer enhancement in presence of a field are available in the literature [10, 11, 31-34].

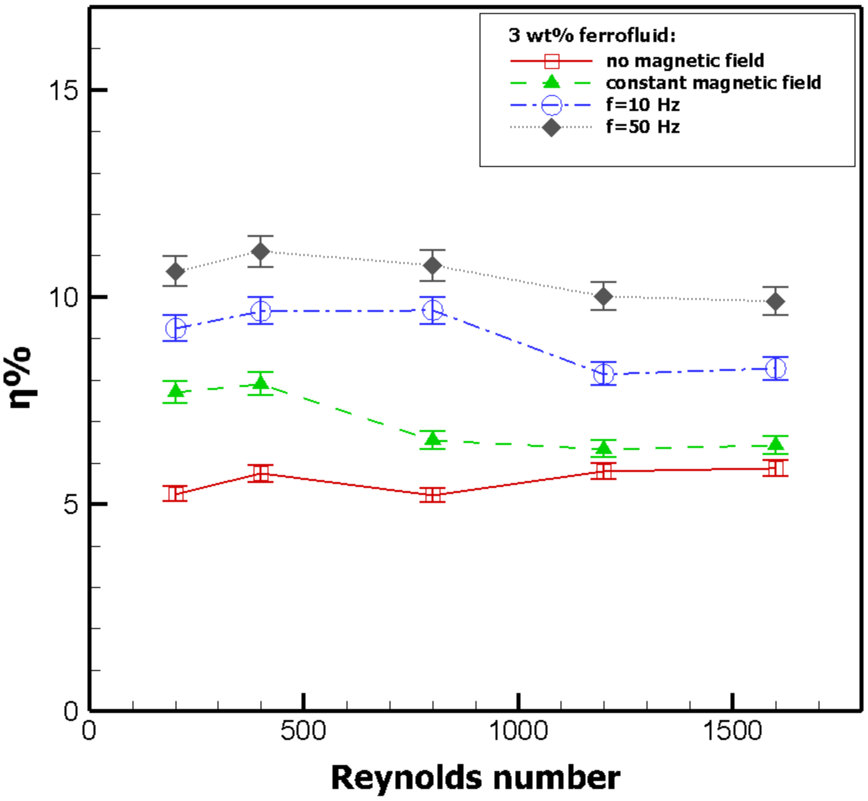


Fig. 14. The enhancement percentage in the heat transfer of 3 wt% ferrofluid under the effect of the constant and alternating magnetic field.

Table 2 .1wt% Fe_3O_4/water nanofluid.

Re	200		400		800		1200		1600	
	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)
No field	451.7	-	590	-	725.8	-	808	-	893.4	-
10 Hz	452.4	0.14	590.7	0.11	726.3	0.07	809/5	0.18	894.9	0.16
50 Hz	452.6	0.18	591.1	0.17	727	0.16	808.9	0.11	894.9	0.17
Constant Field	452.1	0.08	590.6	0.09	726.1	0.05	808.7	0.08	894.1	0.07

η is calculated respect to the case ferrofluid with no magnetic field

Table 3 .3wt% Fe_3O_4/water nanofluid.

Re	200		400		800		1200		1600	
	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)	h_{ave} (W/m^{2}K)	η (%)
No field	470.8	-	617.9	-	756.4	-	845.8	-	936.5	-
10 Hz	488.6	3.79	640.8	3.71	788.5	4.23	864.6	2.21	957.9	2.27
50 Hz	494.8	5.09	649.2	5.06	796.2	5.26	879.6	3.98	972.3	3.82
Constant Field	481.8	2.33	630.6	2.05	765.9	1.25	850.1	0.51	941.5	0.53

η is calculated respect to the case ferrofluid with no magnetic field

To establish a better comparison between different types of magnetic field, the experimental data of the average convective heat transfer coefficient and the enhancement percentage in the heat transfer are given in Table 2 and Table 3 for 1 wt% and 3 wt% ferrofluid, respectively. As seen from Table 2, the results of using 1 wt% ferrofluid, whether constant or alternating magnetic fields, are really close to the results of the case with no magnetic field. In Table 3 it is shown that by decreasing the Reynolds number, the effect of constant magnetic field has been increased for 3 wt% ferrofluid concentration. A small enhancement in heat transfer is also observed when the frequency of the magnetic field increases from 10 to 50 Hz which is negligible for 1 wt% ferrofluid concentration.

7- Conclusions

Convective heat transfer coefficient of ferrofluid under the effect of two kinds of magnetic field (alternating and constant magnetic field) in laminar flow regime was investigated. The performances of three different cases including ferrofluid with no magnetic field, ferrofluid with a constant magnetic field, and ferrofluid with an alternating magnetic field of 10 and 50 Hz for two concentrations (1wt% and 3wt%) were compared to that of the distilled water as the working fluid. The main results can be summarized as:

- Changing the cooling fluid from distilled water to a Fe3O4/water nanofluid, the convective heat transfer coefficient for 3wt% concentration improved by about 5% in the absence of a magnetic field.
- The effect of an alternating and constant magnetic field is noticeable when the nanoparticles concentration increases from 1 wt% to 3 wt%.
- The constant magnetic field and flow rate have an inverse relationship with each other. In the same magnetic field strength as the flow rate decreases, the effect of constant magnetic field increases.
- Changing the frequency of the alternating magnetic field from 10 to 50 Hz, there was a slight enhancement in heat transfer.
- The maximum heat transfer enhancement of 5% compared to the case with no magnetic field occurs when the alternating magnetic field with frequency of 50 Hz is applied.

8- Nomenclature

A	Area, m^2
C_p	specific heat, J/kg ^{0}C
D	diameter, m
h	convective heat transfer coefficient, W/m^{2}K
I	electrical current, A
K	thermal conductivity, W/m K
L	tube length, m
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
Pr	Prandtl number
Q	heat flow, W
q''	heat flux, W/m^2
R	arbitrary function
Re	Reynolds number
T	temperature, ^{0}C
V	voltage, V
X	axial distance from the entrance, m

Greek symbols

δ	uncertainty
η	heat transfer enhancement (%)
μ	viscosity, N.s/m^2
v	arbitrary parameter
ρ	density, kg/m^3
ϕ	nanoparticles volume fraction

Subscript

ave	average
f	fluid
i	inlet
p	nanoparticle
nf	nanofluid
w	wall

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