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New achievements in Fe_3O_4 nanofluid fully developed forced convection heat transfer under the effect of a magnetic field: an experimental study

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ABSTRACT

The fully developed forced convection of Fe3O4 nanofluid inside a copper tube is empirically investigated under the effect of a magnetic field. All the investigations are performed under a laminar flow regime (670≤Re≤1700) and thermal boundary conditions of the tube with uniform thermal flux. The tube is under the effect of a magnetic field at certain points. The aim is to study the effect of various parameters, namely the use of nanofluid, the volume percent of nanoparticles, the Reynolds number of the flow, the constant magnetic field, and the alternating magnetic field with various frequencies in terms of flow behavior. To validate the experiment set-up, distilled water is utilized as the working fluid. The results are compared with Shah's equation, and acceptable agreement is achieved. The results suggest that due to complex convectional flows that developed in the fluid as a result of the Fe_3O_4 nanoparticles–magnetic field interaction, the increased alternating frequency of the magnetic field and the increased volume fraction lead to an increase in the heat transfer to a maximum value of 4.62. As the Reynolds number increases, the rate of the said increase is reduced and reaches 0.29. At a constant Reynolds number, the increased frequency of the alternating magnetic field results in an increased local heat transfer coefficient. However, this increase is unproportional to the increase in frequency. At high frequencies, increased frequency leads to a slight increase in the heat transfer coefficient.

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1. Introduction

Fluids are of great importance in the heating and cooling systems of industries, such as the electrical power, manufacturing, transportation, and electronics industries, and cooling techniques to cool off various high-energy devices are critical. Liquids such as water, ethylene glycol, and oil have limited heat transfer capabilities due to their poor heat transfer properties. In contrast, metals have thermal conductivities of up to three times as great. Therefore, it makes sense to combine these two materials to produce a material with average heat transfer and that has the liquid and thermal conductivity properties of a metal. Fortunately, the emergence of nanofluids and ferrofluids in the heat transfer field is a relatively acceptable and practical solution for potential problems in the future [1, 2]. Magnetic fluids or ferrofluids are colloidal suspensions of magnetic nanoparticles that react to external magnetic fields. This allows the resting place of this solution to be controlled by employing a magnetic field. Fe_3O_4 magnetic nanoparticles can be obtained by mixing ferrous salts II and III in a base solution. Significant research has been conducted on the thermal conductivity of magnetic fluids and ferrofluids. Li et al. [3] examined the measurement of the viscosity and thermal conductivity of magnetic fluids under the effect of external magnetic fields. They studied the effects of volume fractions and surfactants on thermal properties and concluded that

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the increased power of a magnetic field leads to increased viscosity and thermal conductivity, unless the magnetic particles are saturated. Gavili et al. [4] studied the measurement of thermal conductivity in the saturation mode of ferrofluid under the effect of different magnetic field forces and achieved a maximum 200% increase in thermal conductivity. Additionally, there is significant empirical and numerical research on increasing the forced convection of laminar and turbulent flows in relation to such things as the effect of particle type and thickness. The results of such research have led to a considerable increase in the heat transfer coefficient. Li and Xuan [5] studied the forced convection coefficient of nanofluids under turbulent flow conditions and the effects of volume fraction and the Reynolds number on increased convection. Jung et al. [6] investigated the forced convection of Al_2O_3 in the laminar flow inside a cylindrical microchannel. The results showed a 32% increase in convection. Anoop et al. [7] conducted research on the effect of particle size on the forced convection process in the entrance zone. They found that the decreased size of nanoparticles results in an increased convection coefficient. They explained that the increase has greater effects in the entrance zone compared with the fully developed zone. Wen and Ding [8] achieved a remarkable increase in heat transfer by conducting an experiment on water–Al2O3 nanofluid forced convection. Rashidi et al. [9] demonstrated that the discrete particle model is more accurate than the single phase model for simulating nanofluid convection heat transfer. Other researchers have carried out similar research using various nanofluids under laminar flow conditions. They all achieved increased heat transfer [10-16]. Sundar et al. [17] performed an experiment on magnetic nanofluid forced convection under turbulent flow conditions with various volume fractions. They concluded that magnetic particles increase heat transfer by as much as 31%. There is also much research on ferrofluids; however, ferrofluid heat transfer has not been sufficiently investigated. Bovand et al. [18] analyzed the effect of magnetohydrodynamics on nanofluid flow around a triangular obstacle using a finite volume method. They investigated orientations of the obstacle, the Stuart number, and the volumetric concentration of nanoparticles. Among the other factors, they showed that the Stuart number has more of an effect than the Nusselt number. In a different approach, Rashidi et al. [19] applied a finite volume method to simulate the AL_2O_3–water nanofluid flow around a triangular obstacle with magnetohydrodynamic opposition to control the recirculation wake. They demonstrated that stronger magnetic fields reduce the recirculation wake and increase the effect of the magnetic field on the reduction of heat transfer by increasing solid volume fractions. Ashouri et al. [20] undertook a numerical investigation of ferrofluid heat transfer and the Nusselt number in a two-dimensional cavity. They introduced a general relationship for the Nusselt number. The flow between two parallel surfaces exposed to a source line of a dipolar magnetic field demonstrated increased heat transfer [21]. Belayaev and Smorodin described ferrofluid heat transfer in an alternating magnetic field, [22] in light of the external magnetic field frequency and power, layer thickness, and temperature. Li and Juan [23] conducted studies on the effect of uniform and non-uniform magnetic fields on ferrofluid convection at low Reynolds numbers. They concluded that this magnetic field can substantially influence the heat transfer process. Ferrofluid properties, such as viscosity and conductivity, may be exposed to an external magnetic field, thereby precisely controlling the rheological properties. Furthermore, as mentioned earlier, ferrofluids can improve heat transfer. Therefore, this capability has been of great interest to many. However, the forced convection of ferrofluids has not been rigorously studied. Lajvardi et al. [24] investigated heat transfer under the effect of a constant magnetic field. The results revealed a considerable increase in heat transfer; however, there is a small number of such studies. There is empirical research on increasing the forced convection of laminar and turbulent flows in relation to various things, such as the effect of particle type and thickness. The results of such research have led to a substantial increase in the heat transfer coefficient. However, ferrofluid heat transfer has not been sufficiently studied. The ferrofluid heat transfer process under the effect of an alternating magnetic field is very complex. Empirical research would be of great help in studying this phenomenon. Ghofrani et al. [25] investigated the laminar forced convection heat transfer of ferrofluids under an alternating magnetic field and a "developing flow" regime. However, the effect of an alternating magnetic field in a fully developed flow regime is vague. In this research, after procuring and validating the experimentation device, the effect of a constant magnetic field and an alternating magnetic field frequency on Fe_3O_4 fully developed forced convection at various Reynolds numbers and volume fractions of the nanoparticles are investigated. Our approach is different from that in [25] in at least two respects, as follows:

(i) According to the characteristics of the pipe—such as the length and diameter—and the equation $\left(\frac{X_{fd,h}}{D}\right)_{lam} \approx 0.05Re_D$, the flow regime in [25] is a "developing flow". In contrast, our approach is based on a "fully developed flow" (note that the length and diameter of the new pipe are 1248 mm and 4.8 mm, respectively).

(ii) While in [25] the position of the magnet around the pipe is U-shaped, we have used two U-shaped magnets such that the opposite poles of the magnets are against each other.

2. EXPERIMENTAL APPARATUS

2.1 *Experimentation device structure*

An empirical study was conducted to investigate the heat transfer behavior of a fully developed laminar flow in the presence of constant and alternating magnetic fields. The test was carried out on a straight copper tube with an internal diameter of 4.8 mm and a length of 1245 cm. Ten K-type thermocouples were used to register temperature at the input, the output, and other parts of the tube. The uniform thermal flux production mechanism is comprised of a flat wire element, a DC power supply, fireproof tape, and elastomer foam for tube insulation. The flat wire element contains no ferrous materials to deflect the magnetic field existing within the tube. To stabilize the temperature of the fluid entering the test spot, a constant temperature was ensured for the hot flow of the fluid exiting the tube by passing it through a planar thermal converter that is cooled off by a controllable cold-water bath. Six U-shaped non-permanent magnets with ferrous hydroxide as their core coating were used to generate a magnetic field in different areas. The two ends of the magnets were perpendicular to the axis and each two magnets were positioned across from one another with the opposite poles facing each other. This was done to increase the intensity of the magnetic field. The U-shaped core is made of appropriate magnetic materials for generating an alternating magnetic field. To obtain a magnetic field around the copper tube, 2000 turns of number 20 copper wires were wound around the U-shaped core. Figures 1 and 2 demonstrate the winding shape and the way the wires were positioned on the core and the schematics of how the magnet was positioned on the tube. A digital circuit was designed to control the magnetic core flow. The microcontroller of this circuit can vary the magnetic field's frequency and power. This circuit is the most important part in which pulses with specified durations and alternating magnetic fields were generated and applied to the test section to investigate the effects of frequency on increased heat transfer. What is meant by an oscillating magnetic field is a magnetic field that is alternately cut off and then comes back on. The oscilloscope display of a magnetic field waveform is depicted in Figure 1.

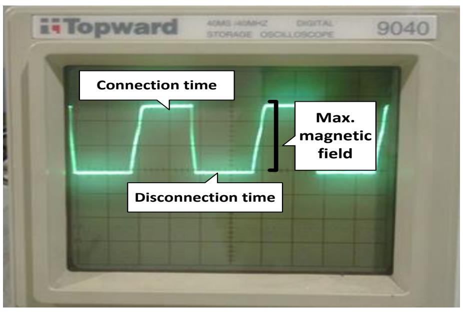


Fig.1. Oscilloscope display of a magnetic field waveform

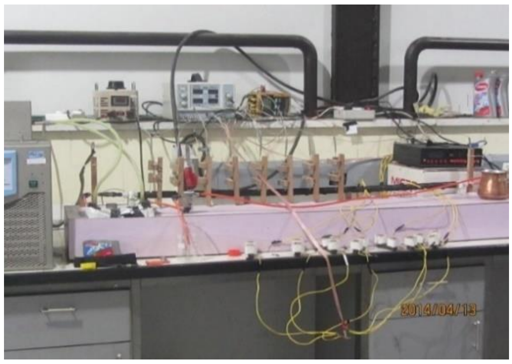


Fig. 2 Experimentation device

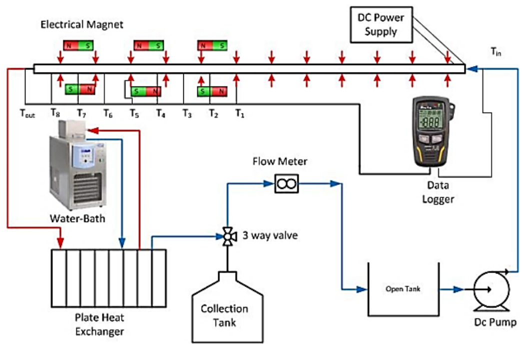


Fig. 3. Experimentation device schematic

The inverse of the connection or disconnection time of the magnetic field is considered to be the magnetic field frequency.

$$f = \frac{1}{T} \quad (1)$$

In this experiment, a 700 G magnetic field was applied to the ferrofluid in constant and oscillating forms with three frequencies of 10 Hz, 20 Hz, and 50 Hz. A magnetic shield was used to eliminate the disturbance exerted on the thermocouple by the alternating magnetic field. Figure 2 and Figure 3 show the experimentation device and its schematic.

2.2 *Ferrofluid synthesis and its properties*

The co-precipitation method [26] was employed in making the magnetic component of the ferrofluid. This method involves chemical sedimentation in an organic or water solvent. There are several different ways to perform this process. The most conventional method is that employed by Khalafalla and Reimers [27]. This process involves the sedimentation of ferrous oxide particles via the reaction of ferrous salts with hydroxide (HO). The reaction governing this method is shown in equation 2. According to this reaction, iron (II) and iron (III) chlorides react in the presence of a base, and the resulting magnetite is obtained in the form of a black sediment.

$$FeCl_2 + 2FeCl_3 + 8NH_4OH \rightarrow Fe_3O_4 + 4H_2O + 8NH_4Cl \quad (2)$$

2.3 Adding surfactant

To procure ferrofluid, it is necessary that the particles maintain their small size and not become attached to each other so that the mixture remains as a suspension. To this end, another category of materials called surfactants was used. Surfactants prevent the particles from getting too close to each other. The dual nature of these molecules gives rise to specific properties that allow them to dissolve in water gathering on the water–air common surface or between two surfaces from two different phases, thereby reducing surface tension. For instance, in this case, surfactants are connected to the colloid from one end and are close to the solution at the other end. Therefore, the ends inside the solution are homonymous, thus causing repulsion among colloids. As a result, their accumulation and attachment is prevented, and the solution maintains its magnetic property [28]. In this work, citric acid is used as the surfactant for the water-based ferrofluid. Particles size measurement indicating that the obtained solution is a stable mixture of magnetic particles with the average diameter of 25 nm.

2.4 Registering and analyzing data

To analyze heat transfer, the convection coefficient (h) was calculated as follows using empirical data. After measuring the fluid volume discharge using equation 3, fluid flow average velocity was obtained from equation 4 by calculating the tube's section.

$$Q = \frac{\forall}{t} \quad (3)$$

$$U = \frac{Q}{A} \quad (4)$$

Considering the tube as a control volume and applying energy conservation law, the real thermal flux applied to the external wall of the tube was calculated using equation 5.

$$q'' = \frac{D\rho cU(T_{out} - T_{in})}{4L}. \quad (5)$$

Knowing the thermal flux in the tube's external wall, the average temperature of each x was obtained using equation 6 and by considering energy conservation for each length of x.

$$T_m = \frac{4xq''}{D\rho cU} + T_{in} \quad (6)$$

Finally, using the Nu number relationship, the local Nu was obtained according to equation 7. The local h value was calculated using equation 8.

$$Nu_{exp} = \frac{q''D}{k(T_s - T_m)} \quad (7)$$

$$h_{exp} = \frac{k}{D} Nu_{exp} \quad (8)$$

In the above equations, the thermophysical properties of Fe_3O_4 nanofluid—such as density, specific heat capacity, the thermal conductivity coefficient, and viscosity—were measured with great precision using calibrated devices. To measure the thermal properties and viscosity, a KD2 device and an Ostwald viscometer were used. Table 1 shows the measured values and the precision of the devices. It should be mentioned that all necessary principles, including the equipment's precision, accuracy, repeatability, reproducibility, and calibration, were observed for the measurements in accredited laboratories.

2.5 Evaluating the setup

The system reliability and precision were examined before the main experiments began. In line with this, the empirical measurement results were compared with those of Shah's equation for laminar flow under constant-flux boundary conditions with distilled water (working fluid). Equations 9–11 [29] were used to empirically calculate local h under similar conditions. The results in Figure 4 are in proper agreement with the prediction of Shah's equation at 10 l/h volumetric flow rate, indicating the reliability of the empirical results using this experimentation device.

Table 1. Nanofluid properties and their precision

Properties	Fe_3O_4– 1.25%	Fe_3O_4– 2.5%	Fe_3O_4– 5%	Accuracy
$\rho(kg/m^3)$	1051.28	1104.19	1208.84	± 0.001 g/cm^3
Cp(J/kg k)	4144.6	4107.1	4022.0	± 0.01 J/kg k
K(W/m k)	0.612	0.623	0.665	± 0.01 w/m k
$\nu(m^2/s)$	1.1E-06	1.2E-06	1.3E-06	1%

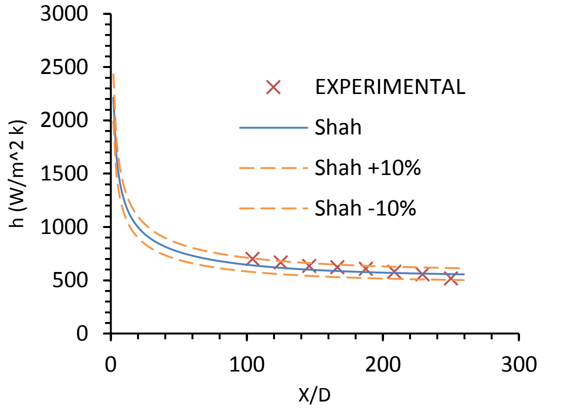


Fig. 4. Comparison between the local convection coefficient of distilled water and Shah's equations at 10 lit/h volumetric flow rate

$$h_{theory} = \frac{k}{D} Nu_{theory} \tag{9}$$

$$Nu_{theory} = \begin{cases} 1.302x^{*-1/3} - 1, & x^* \leq 0.00005 \\ 1.302x^{*-1/3} - 0.5, & 0.00005 \leq x^* \leq 0.0015 \\ 4.364 + 8.68(10^3 x_*)^{-0.506} \exp(-41x_*), & x_* \geq 0.001 \end{cases} \tag{10}$$

$$x_* = \frac{x/D}{RePr} \tag{11}$$

2.6 Error analysis and uncertainty

Real errors in empirical data are always somewhat vague and involve uncertainty. Therefore, it should be determined to what extent a certain observation is devoid of certainty. There are two types of errors in measurement—random and systematic. What is of interest in terms of uncertainty is random error. However, certain systematic errors randomly affect measurement and should be taken into consideration in calculations [30]. Here, uncertainty analysis was performed using the method developed by Kline and McClintock [31], and uncertainty was calculated to be 0.7% and 1.6%, respectively, for Re and h.

3. Results and discussion

After evaluating the experimentation system using distilled water, various experiments were conducted for three different volume fractions of the nanofluid (1.25%, 2.5%, and 5%) and under five different modes of the magnetic field—namely no magnetic field, a constant magnetic field, and an alternating magnetic field with 10 Hz, 20 Hz, and 50 Hz frequencies. It should be noted that different Reynolds numbers were obtained for ferrofluids with different volume percentages due to changes in ferrofluid properties, such as viscosity, for constant discharges of flow. Therefore, the fluids were compared in constant volume discharges (10 l/h, 20 l/h, and 30 l/h). As in constant flow rates the characteristics of a ferrofluid, such as viscosity, are not fixed, different Reynolds numbers will be obtained. Considering the viscosity of ferrofluid for various volume concentrations and flow rates, the range of Reynolds numbers is from 670 to 1700. Of course, the variations in the Reynolds number was investigated in each case, and they turned out to be negligible. The obtained results are presented and analyzed in this section.

3.1 Investigating the effect of Fe_3O_4 nanofluid on h in comparison with pure water in the absence of a magnetic field

At first, the experiment was carried out with three different volumetric flow rates and three different volume fractions in the absence of a magnetic field. Figure 5 shows the mean convection coefficient diagram against dimensionless length (x/D) at the volumetric flow rate of 20 l/h. The results indicate that the use of the ferrofluid considerably improves convection. The improvement is more noticeable for higher volume fractions.

The increased heat transfer is attributed to mechanisms such as particle transfer, viscosity gradient, and Brownian motion in nanofluids [8, 10, 12, 13]. Chaos in thermal boundary conditions and an increased thermal conductivity coefficient are among the major reasons why nanofluids improve heat transfer. Given the energy equation in the boundary condition and the approximate solution of the convection coefficient (k/δ_t), adding Fe_3O_4 particles to pure water leads to an increased heat transfer coefficient for the Fe_3O_4 nanofluid, thus increasing h. Another factor that can result in this improvement is the turbulent motion of superfine particles that speed up the heat exchange process. Further, it has been observed that with the increased volume percent of ferroparticles, there is more improvement in convection. This may be due to the intensification of the above factors. Consequently, the mentioned factors account for the increased heat transfer of the ferrofluids in the absence of a magnetic field.

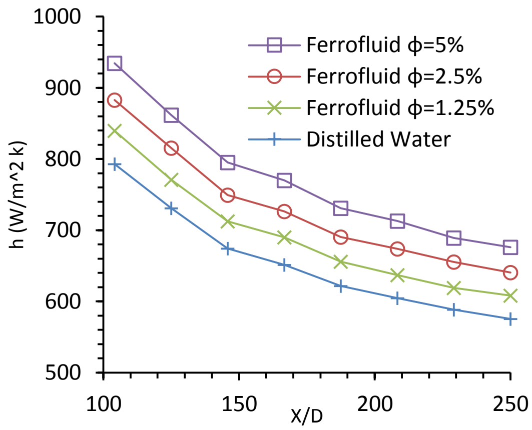


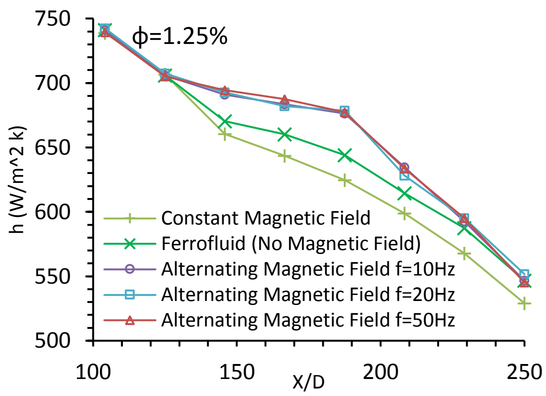
Fig. 5. Variations in the mean convection of Fe_3O_4 nanofluid and distilled water with a 20 l/h volumetric flow rate and variable volume fractions

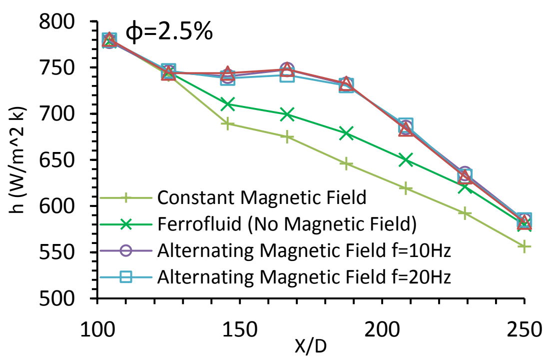
3.2 Investigating the effect of a magnetic field on h in Fe_3O_4 nanofluid flow

To study the effect of the magnetic field on h, after each experiment for the Fe_3O_4 nanofluid with a specified volume fraction and volumetric flow rate in the absence of a magnetic field, four other experiments were conducted in the presence of a magnetic field. One of these experiments was carried out with a constant magnetic field and the other three experiments were carried out with an alternating magnetic field (10 Hz, 20 Hz, and 50 Hz). The on/off durations of the magnetic field were equal. The inverse of the period was introduced as the magnetic field frequency. All experiments were done with three volumetric flow rates (10 l/h, 20 l/h, and 30 l/h) and three volume fractions (1.25%, 2.5%, and 5%). The results are shown in Figures 6 to 8.

In the case of using a constant magnetic field, once the fluid is exposed to the magnetic field, a decrease in the convection coefficient may be observed at large axial distances from the location where the fluid enters. The reason for this reduction is a constant pressure drop and resistance against the flow passing through, eventually leading to decreased diffusion and convection.

The obtained results suggest that the alternation of the magnetic field contributes to increasing h compared with the cases where there was no magnetic field or a constant magnetic field. The increased frequency of an alternating magnetic field leads to no considerable increase in h. However, the effect of the alternating magnetic field increases at low volumetric flow rates. Furthermore, the alternating magnetic field has a considerable effect at high volume fractions compared with low volume fractions.





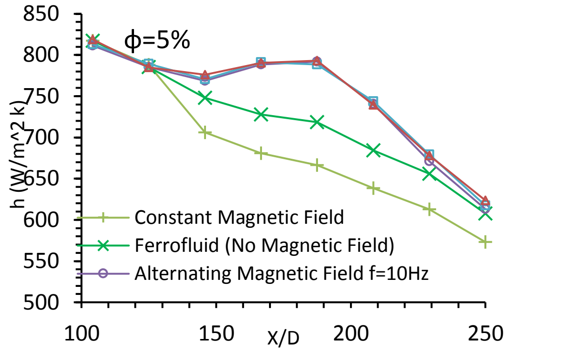


Fig. 6. Ferrofluid convection coefficient variations at the volume discharge of 10 l/h in the absence and presence of constant and oscillating magnetic fields

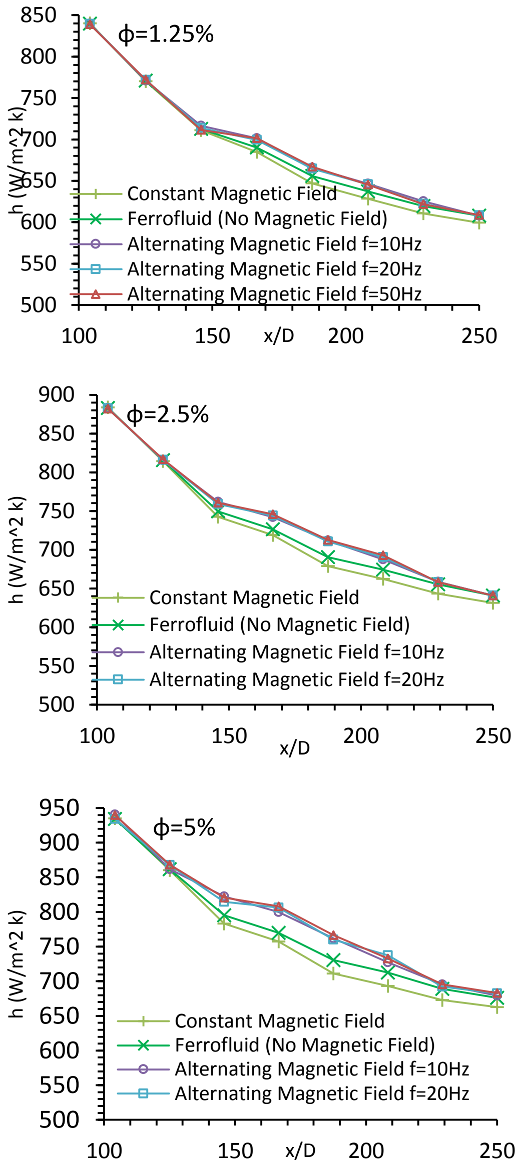


Fig. 7. Ferrofluid convection coefficient variations at the volume discharge of 20 l/h in the absence and presence of constant and oscillating magnetic fields

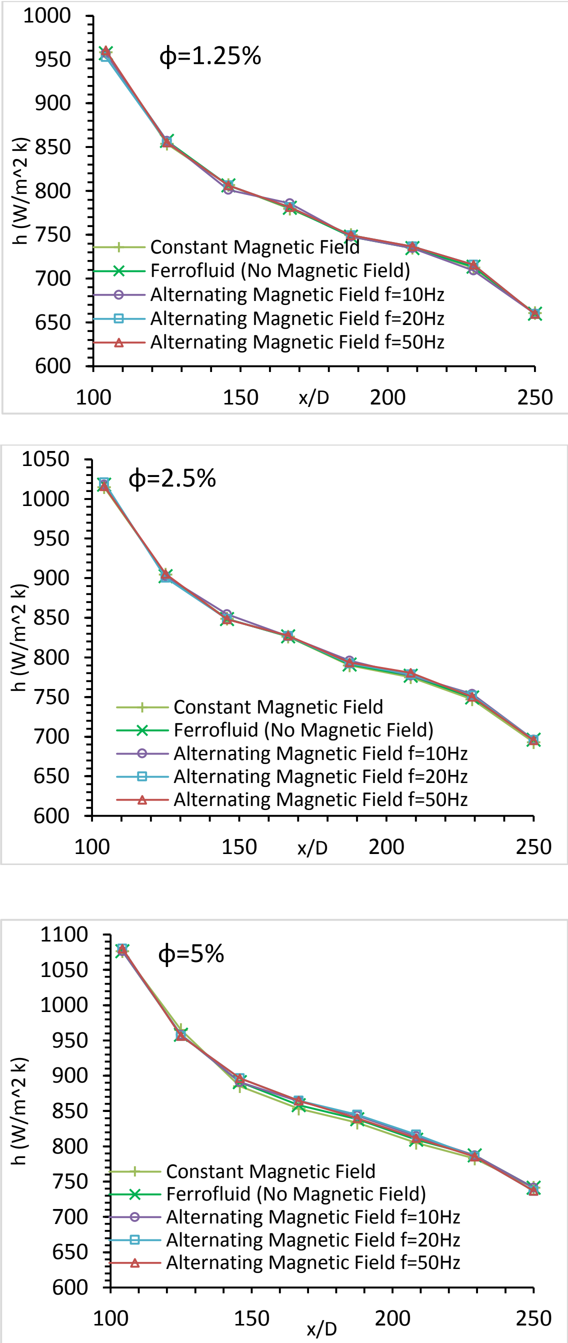


Fig. 8. Ferrofluid convection coefficient variations at the volume discharge of 30 l/h in the absence and presence of constant and oscillating magnetic fields

3.3 *Decreased and increased heat transfer coefficient theory*

The following relationship was used to calculate the percentage of heat transfer improvement in the second mode compared to the first mode:

$$\eta = \frac{h_2 - h_1}{h_1} \times 100. \quad (11)$$

Thus, the average improvement of the ferrofluid convection coefficient percentage was compared in the absence and presence of a magnetic field. The average improvement of the ferrofluid convection coefficient percentage in the absence of a magnetic field was compared to distilled water; the results are shown in Table 2. The average improvement of the ferrofluid convection coefficient percentage in the presence of a magnetic field was compared to distilled water and was calculated compared to the ferrofluid; the results are shown in Table 2.

In all states, the convection coefficient was proportional to k/δ_t, where k is thermal conductivity and δ_t is the thickness of the thermal boundary condition. At the same time, when Fe_3O_4 particles are added to water the result is increased h, and the fluid's heat transfer coefficient increases. To date, contradictory results regarding the effect of a constant magnetic field have been obtained in various studies [23-25, 32]. It seems that the power of the applied magnetic field considerably affects improved or decreased convection. The accumulation of nanoparticles along the magnetic field leads to increased thermal conduction because low-resistance paths take shape. This was also observed in previous studies [3, 4]. Moreover, when a magnetic field is applied, the interactions between the masses and the fluid flow increase, and the disruption and turbulence of the boundary layer also increase. Increased thermal conduction and boundary layer turbulence makes for improved convection. However, applying a constant magnetic field causes increased fluid viscosity, thus preventing the fluid from flowing. This phenomenon slows down fluid motion and thus reduces convection [3, 33-35]. In general, it seems that there is a competition among the mechanisms for increased viscosity, increased thermal conduction, and thermal boundary layer turbulence. Increased viscosity is probably dominant for lower power magnetic fields compared to higher power magnetic fields where increased thermal conduction coefficient and boundary layer turbulence are the influential factors. The slowing down of increased viscosity and fluid motion also account for decreased convection outside the area where the magnetic field is applied because it is clear that the fluid flow continues to be slow past this area.

Investigating the magnetic field distribution using commercial software, as shown in Figure 9, demonstrates how the magnetic field is distributed in this study. It is completely clear that the direction of the magnetic field is perpendicular to the pipe axis between the opposing poles of the winding. This may give rise to the above-mentioned phenomena.

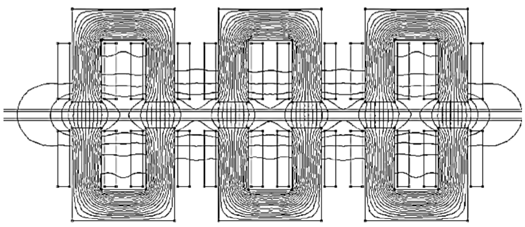


Fig. 9. Constant magnetic flux lines around the magnets

Table 2. Average improvement of ferrofluid convection coefficient percentage compared to distilled water at volume discharges of 10, 20, and 30 l/h

Alternating Magnetic Field f=50Hz	Alternating Magnetic Field f=20Hz	Alternating Magnetic Field f=10Hz	Constant Magnetic Field	Ferrofluid (No Magnetic Field)	Volume Fraction (%)	Volumetric Flow Rate
3.08	2.03	1.97	-2.04	5.79	1.25	
3.4	3.3	3.42	-3.11	11.77	2.5	
4.62	4.4	4	-4.74	17.57	5	**10 l/h**
0.63	0.60	0.77	-0.83	5.57	1.25	
1.33	1.19	1.12	-1.1	11.33	2.5	
2.4	2.1	2	-1.63	17.72	5	**20 l/h**
0.12	0.02	0.01	-0.01	5.53	1.25	
0.1	0.1	0.24	-0.17	11.46	2.5	
0.14	0.29	0.23	-0.29	17.37	5	**30 l/h**

Once the alternating magnetic field is applied, convection coefficient values are improved. An increased thermal conduction coefficient under the effect of the oscillating magnetic field can be introduced as a reason for this improvement. In addition, the increased motion of particles and boundary layer disruption and turbulence are also considered important factors for the improved convection coefficient [5-8, 10, 12, 13, 36]. Once the oscillating magnetic field is applied, the collisions among magnetic particles and the interactions among the particles and the fluid and between the particles and the pipe surface increase and the heat transfer process improves. Nonetheless, with the increased motion of the particles, more particles are probably absorbed into the wall, causing greater boundary layer disruption and turbulence.

It can be observed that there is a decrease in improved heat transfer outside the area where the magnetic field is applied. The decreased heat transfer may be attributed to the change in the flow pattern when the fluid is in the area where there is no magnetic field.

Comparing the diagrams with different Reynolds numbers reveals that the effects of the magnetic field, whether constant or oscillating, may be observed with low Reynolds numbers such that the magnetic field does not affect the heat transfer process with high Reynolds numbers. With decreased Reynolds numbers and flow discharge, the effects of the presence of the magnetic field come to light. The reason for this may be the greater chance of magnetic particles for absorption, motion, and thermal boundary layer disruption and turbulence at low velocities of fluid flow. As the flow velocity increases, the particle absorption process becomes more difficult and the reasons behind the improvement of or decrease in heat transfer play less important roles.

Further, comparing the volume thickness of the ferrofluid also demonstrates that, as expected, improved heat transfer increases under the effect of the oscillating magnetic field, as does decreased heat transfer under the effect of the constant magnetic field. This is because the particle absorption mechanism of the magnetic field, particle motion, boundary layer disruption, and formation of larger sized masses are intensified. In general, it may be stated that the magnetic field effects are more substantial in higher volume percentages and with lower Reynolds numbers.

The above diagrams show that a change in the oscillation frequency has no effect on convection except for a negligible value for low Reynolds numbers and a high volume percent. Changed frequency probably does not have a considerable effect on particle motion or disrupts the thermal boundary layer to the same extent. This is because the magnetic particles are equally affected by the oscillating magnetic fields with different frequencies.

4. Conclusion

Without an external magnetic field, the magnetic fluid convection is more effective compared with the base fluid convection. This is, of course, expected due to the change in the fluid’s properties. The volume percent of the ferrofluid contributes greatly to heat transfer improvement in that increased volume percent increases heat transfer improvement because greater variations in fluid properties are observed with increased volume percent. As the results suggest, applying a magnetic field substantially affects the ferrofluid convection process. These effects are manifested in changes in fluid thermal conduction, fluid viscosity, motion and interaction among magnetic particles, the formation of magnetic masses, and thermal layer disruption and turbulence.

Investigating the effect of the constant magnetic field reveals that the heat transfer coefficient decreases compared with the case where there is no magnetic field. As predicted, this decrease is, of course, more visible in higher volume fractions of the fluid. It can be seen that the magnetic field has a smaller effect at high Reynolds numbers compared with low Reynolds numbers. In fact, the magnetic field plays a more effective role at low Reynolds numbers because the fluid velocity is lower at low Reynolds numbers; therefore, the magnetic field has more time to absorb magnetic particles. It can also be seen that once the magnetic field is cut off, the decreasing heat transfer trend continues. Imposing the constant magnetic field results in an increase in fluid viscosity and thus reduced flow. This phenomenon decreases the convection heat transfer. However, with respect to the effects of the alternation of the magnetic field, it should be said that a relative improvement in heat transfer can be observed. The lower the Reynolds number and the higher the fluid's volume percent, the more conspicuous the improvement. The alternation frequency causes no particular change in heat transfer improvement. At lower Reynolds numbers, increased magnetic field intensity results in a slight improvement in heat transfer. It may also be seen that once the magnetic field is cut off, the effects of improvement caused by the magnetic field gradually decrease. In the case of alternating magnetic fields, sequences of nanoparticles launched from the interior of the fluid are formed that increase the convection heat transfer. By cutting off the magnetic field, nanoparticles will be spread again in the fluid and their Brownian motions will increase the Nusselt number.

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Nomenclature

C_p Specific heat (J/KgK)
D Diameter (m)
f Frequency (Hz)
$\overline{h}$ Average convective heat transfer coefficient along the tube (W/m^2K)
h Convective heat transfer coefficient (W/m^2K)
I Current (A)
k Thermal conductivity (W/mK)
L Tube length (m)
m Mass (Kg)
$\dot{m}$ Mass flow rate (Kg/s)
Nu Nusselt number (hD/k)
Pr Prandtl number ($C_p\mu/k$)
q'' Heat flux (W/m^2)
q Heat flow (W)
T Temperature (°C)
t Time(s)
V Voltage (V)
∀ Volumetric flow rate
x Axial distance from the inlet of the tube (m)
U Velocity (m/s)

Greek Letters

μ Viscosity (Pa s)
τ Alternating magnetic field connection time (s)
φ Volume fraction
ρ Density (Kg/m^3)
η Heat transfer enhancement percentage in comparison with distilled water
δ Boundary layer thickness (m)

Subscripts

in Inlet
Fe Ferrofluid
M Middle parameter
out Outlet
s Wall
p Particle
w Water

References

[1] Z. M. Zhang, *Nano/microscale heat transfer*: McGraw-Hill New York, 2007.

[2] S. K. Das, S. U. Choi, W. Yu, T. Pradeep, *Nanofluids: science and technology*: Wiley-Interscience Hoboken, NJ, 2008.

[3] Q. Li, Y. Xuan, J. Wang, Experimental investigations on transport properties of magnetic fluids, *Experimental Thermal and Fluid Science,* Vol. 30, No. 2, pp. 109-116, 2005.

[4] A. Gavili, F. Zabihi, T. D. Isfahani, J. Sabbaghzadeh, The thermal conductivity of water base ferrofluids under magnetic field, *Experimental Thermal and Fluid Science,* Vol. 41, pp. 94-98, 2012.

[5] Q. Li, Y. Xuan, J. Wang, Investigation on convective heat transfer and flow features of nanofluids, *Journal of Heat transfer,* Vol. 125, pp. 151-155, 2003.

[6] J.-Y. Jung, H.-S. Oh, H.-Y. Kwak, Forced convective heat transfer of nanofluids in microchannels, *International Journal of Heat and Mass Transfer,* Vol. 52, No. 1, pp. 466-472, 2009.

[7] K. Anoop, T. Sundararajan, S. K. Das, Effect of particle size on the convective heat transfer in nanofluid in the developing region, *International Journal of Heat and Mass Transfer,* Vol. 52, No. 9, pp. 2189-2195, 2009.

[8] D. Wen, Y. Ding, Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions, *International*

Journal of Heat and Mass Transfer, Vol. 47, No. 24, pp. 5181-5188, 2004.

[9] S. Rashidi, M. Bovand, J. A. Esfahani, G. Ahmadi, Discrete particle model for convective AL 2 O 3–water nanofluid around a triangular obstacle, *Applied Thermal Engineering,* Vol. 100, pp. 39-54, 2016.

[10]S. Zeinali Heris, S. G. Etemad, M. Nasr Esfahany, Experimental investigation of oxide nanofluids laminar flow convective heat transfer, *International Communications in Heat and Mass Transfer,* Vol. 33, No. 4, pp. 529-535, 2006.

[11]K. S. Hwang, S. P. Jang, S. U. Choi, Flow and convective heat transfer characteristics of water-based Al< sub> 2</sub> O< sub> 3</sub> nanofluids in fully developed laminar flow regime, *International Journal of Heat and Mass Transfer,* Vol. 52, No. 1, pp. 193-199, 2009.

[12]Y. Ding, H. Alias, D. Wen, R. A. Williams, Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids), *International Journal of Heat and Mass Transfer,* Vol. 49, No. 1, pp. 240-250, 2006.

[13]D. Kim, Y. Kwon, Y. Cho, C. Li, S. Cheong, Y. Hwang, J. Lee, D. Hong, S. Moon, Convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions, *Current Applied Physics,* Vol. 9, No. 2, pp. e119-e123, 2009.

[14]U. Rea, T. McKrell, L.-w. Hu, J. Buongiorno, Laminar convective heat transfer and viscous pressure loss of alumina–water and zirconia–water nanofluids, *International Journal of Heat and Mass Transfer,* Vol. 52, No. 7, pp. 2042-2048, 2009.

[15]S. Tahir, M. Mital, Numerical investigation of laminar nanofluid developing flow and heat transfer in a circular channel, *Applied Thermal Engineering,* Vol. 39, pp. 8-14, 2012.

[16]S. Z. Shirejini, S. Rashidi, J. Esfahani, Recovery of drop in heat transfer rate for a rotating system by nanofluids, *Journal of Molecular Liquids,* Vol. 220, pp. 961-969, 2016.

[17]L. Syam Sundar, M. Naik, K. Sharma, M. Singh, T. C. Siva Reddy, Experimental investigation of forced convection heat transfer and friction factor in a tube with Fe< sub> 3</sub> O< sub> 4</sub> magnetic nanofluid, *Experimental Thermal and Fluid Science,* Vol. 37, pp. 65-71, 2012.

[18]M. Bovand, S. Rashidi, J. Esfahani, Optimum Interaction Between Magnetohydrodynamics and Nanofluid for Thermal and Drag Management, *Journal of Thermophysics and Heat Transfer,* pp. 1-12, 2016.

[19]S. Rashidi, M. Bovand, J. Esfahani, Opposition of Magnetohydrodynamic and AL 2 O 3–water nanofluid flow around a vertex facing triangular obstacle, *Journal of Molecular Liquids,* Vol. 215, pp. 276-284, 2016.

[20]M. Ashouri, B. Ebrahimi, M. Shafii, M. Saidi, M. Saidi, Correlation for Nusselt number in pure magnetic convection ferrofluid flow in a square cavity by a numerical investigation, *Journal of Magnetism and Magnetic Materials,* Vol. 322, No. 22, pp. 3607-3613, 2010.

[21]R. Ganguly, S. Sen, I. K. Puri, Heat transfer augmentation using a magnetic fluid under the influence of a line dipole, *Journal of Magnetism and Magnetic Materials,* Vol. 271, No. 1, pp. 63-73, 2004.

[22]A. Belyaev, B. Smorodin, Convection of a ferrofluid in an alternating magnetic field, *Journal of applied mechanics and technical physics,* Vol. 50, No. 4, pp. 558-565, 2009.

[23]Q. Li, Y. Xuan, Experimental investigation on heat transfer characteristics of magnetic fluid flow around a fine wire under the influence of an external magnetic field, *Experimental Thermal and Fluid Science,* Vol. 33, No. 4, pp. 591-596, 2009.

[24]M. Lajvardi, J. Moghimi-Rad, I. Hadi, A. Gavili, T. Dallali Isfahani, F. Zabihi, J. Sabbaghzadeh, Experimental investigation for enhanced ferrofluid heat transfer under magnetic field effect, *Journal of Magnetism and Magnetic Materials,* Vol. 322, No. 21, pp. 3508-3513, 2010.

[25]A. Ghofrani, M. Dibaei, A. Hakim Sima, M. Shafii, Experimental investigation on laminar forced convection heat transfer of ferrofluids under an alternating magnetic field, *Experimental Thermal and Fluid Science,* 2013.

[26]H. Bagheri, O. Zandi, A. Aghakhani, Extraction of fluoxetine from aquatic and urine samples using sodium dodecyl sulfate-coated iron oxide magnetic nanoparticles followed by spectrofluorimetric determination, *Analytica chimica acta,* Vol. 692, No. 1, pp. 80-84, 2011.

[27]S. Khalafalla, G. Reimers, Preparation of dilution-stable aqueous magnetic fluids, *Magnetics, IEEE Transactions on,* Vol. 16, No. 2, pp. 178-183, 1980.

[28]L. Shen, P. E. Laibinis, T. A. Hatton, Bilayer Surfactant Stabilized Magnetic Fluids: Synthesis and Interactions at Interfaces, *Langmuir,* Vol. 15, No. 2, pp. 447-453, 1999/01/01, 1998.

[29]A. Bejan, A. D. Kraus, *Heat transfer handbook*: John Wiley & Sons, 2003.

[30]E. R. Eckert, R. J. Goldstein, *Measurements in heat transfer*: Taylor & Francis, 1976.

[31]S. J. Kline, F. McClintock, Describing uncertainties in single-sample experiments, *Mechanical engineering,* Vol. 75, No. 1, pp. 3-8, 1953.

[32]R. Azizian, E. Doroodchi, T. McKrell, J. Buongiorno, L. Hu, B. Moghtaderi, Effect of magnetic field on laminar convective heat transfer of magnetite nanofluids, *International Journal of Heat and Mass Transfer,* Vol. 68, pp. 94-109, 2014.

[33]J. Jolivet, R. Massart, J. Fruchart, Synthesis and physicochemical study of non-surfactant magnetic colloids in an aqueous-medium, *Nouveau Journal De Chimie-New Journal of Chemistry,* Vol. 7, No. 5, pp. 325-331, 1983.

[34] D. Wagh, A. Avashia, On the viscosity of a magnetic fluid, *Journal of magnetism and magnetic materials,* Vol. 153, No. 3, pp. 359-365, 1996.

[35] H. Kargarsharifabad, M. Falsafi, Numerical Study of Ferrofluid Forced Convection Heat Transfer in Tube with Magnetic Field, *Journal of Computational Method in Engineeering,* Vol. 34, No. 1, pp. 11-25, 2015.

[36] H. Kargarsharifabad, M. Falsafi, Numerical modeling of internal convection heat transfer of magnetic fluid in the pulse magnetic field and different time frequencies, *Modares Mechanical Engineering,* Vol. 15, No. 6, pp. 91-98, 2015.