Investigation of heat transfer enhancement using ferro-nanofluids (Fe₃O₄/water) in a heated pipe under the application of magnetic field

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Abstract
Different volume concentrations (1.2, 0.6, 0.3 wt%) of Fe₃O₄/water nanofluids and for different Reynolds number (Re) varying from 2180 to 9160 were used experimentally. The aim of work is to study the effect of applying various magnetic field intensity 15.1, 30.3, 45.5 mT on heat transfer enhancement in a horizontal pipe heated with constant heating flux of 420 W. Results showed that Nusselt number (Nu) increases with increasing Re for the nanofluids and water regardless the presence or absence of the magnetic field. Also, higher values were obtained than water. The average increase in Nu for Fe₃O₄-nanofluids is 16.7% relative to water when the magnetic field is not applied. However, the average increase in heat transfer coefficient and Nusselt number are 9.4%, 26.1%, 31.3% and 8.8%, 13.1%, and 23.9% in the presence of magnetic field (Φ = 15.5, 30.3, 45.5)mT compared to the absence of magnetic field and base fluid water, respectively. Furthermore, pressure drop increases with the increase of Reynolds number and magnetic field strength. It can be concluded that the magnetic field has a big effect on the thermal transfer performance of Fe₃O₄/water nanofluid when compared with the thermal motion of magnetic nanoparticles. Finally, it is found that the performance factor is above unity in the presence and absence of magnetic field strength. This means that Nusselt number enhancement is higher than friction changes, which indicates the applicability of the heated pipe in the improvement of heat transfer. These results can be useful for enhancing heat transfer in many engineering applications such as heat exchangers, medical devices, and electronic devices.

Keywords
Nanofluid (Fe₃O₄/water-ethanol), Nusselt number, volume concentration, heat transfer, magnetic field

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Introduction
Nanofluids are a mixture of base fluid and nanoparticles, commonly, less than 100 nm in size. Nanofluids are a new class of nanomaterials that offer significant advantages of superior thermophysical properties with higher values of base numbers (Nusselt, Prandtl, Darcy) when compared to base fluids. Due to high thermal conductivity, nanofluids can be used in many engineering applications, for example, automotive sector, medical devices, and electronic devices.
Experimental work of the effect of magnetic field on the heat transfer enhancement using nanofluids was carried out by several researchers. Among them, the work done by Nakharintr and Naphon\(^1\) in which they studied the effect of applying nanofluids single jet on a mini-channel heat sink under the application of magnetic field on heat transfer characteristics. It was found that Nu increased with the application of magnetic field, furthermore, and at higher values of magnetic field strength. Naphon and Wiriyasart\(^2\) investigated experimentally the combined effect of pulsating flow and magnetic field on the heat transfer and flow characteristics in the micro-fins heated tube at temperature 20°C and heating flux (120–160 W) using nanofluids. Different values of Re (1000–2400) and nanofluids concentrations of 0.25% and 0.50% by volume were used in the experimental work. Results showed that Nu increases under the application of magnetic field and pulsating flow by a value of 6.23% higher than those without magnetic field effect. Also, Nu increases with higher values of magnetic field strength and nanofluids concentration, respectively. Karmi et al.\(^3\) investigated the effect of particle volume fraction, temperature, and magnetic field strength on the thermal conductivity of hematite (Fe\(_2\)O\(_3\)) and magnetite (Fe\(_3\)O\(_4\)) water based nanofluids. Volume concentration range between 0% and 4.8% and the temperature range of 20°C–60°C were used. It was found that thermal conductivity is inversely proportional with temperature in the presence of magnetic field. Also, Fe\(_3\)O\(_4\) nanofluids showed higher values of thermal conductivity than Fe\(_2\)O\(_3\) nanofluids. Furthermore, a relationship between thermal conductivity of iron oxide magnetic nanofluids and volume fraction, temperature, and magnetic field strength was developed. Huminic et al.\(^4\) investigated experimentally the effects of temperature (20°C–70°C range), weight concentration (0.5, 1.0, 2.0, and 4.0 wt% range) on thermal conductivity of iron oxide/water nanofluids. Results showed that nanofluids have high values of thermal conductivity at higher values of volume concentration and temperature, respectively compared with base fluid.

Numerical analysis research papers on heat transfer enhancement using nanofluids under the application of magnetic field were found in the open literature. Soltnipour et al.\(^5\) numerical work was to investigate the influence of applying different circumferential angles of magnetic field on heat transfer enhancement in a curved pipe. It was found that at low magnetic numbers, the optimal circumferential location of the magnetic source is \(\phi_{\text{opt}} = 180°\) which leads to the maximum heat transfer enhancement, and for high magnetic numbers, the optimal operating condition occurs at \(\phi = 0°\) and \(\phi = 60°\) depending on the magnetic number. Singh et al.\(^6\) investigation of ferrofluid flow through a mini-channel in the presence of both constant and alternating magnetic field led to an increase of 17.41% in heat transfer. More work by Singh et al.\(^7\) was carried out but on different application in which they worked on developing a ferrofluid based heat exchanger for PVT systems. Similar results were obtained. Bezaatpour and Goharkhah\(^8\) numerical investigation showed that Nusselt number increased with the increase of volume fraction and magnetic field strength when they used iron oxide/water nanofluids in the heat sink with the presence

Of magnetic field, Selimefendigil et al.\(^9\) studied numerically the effects of volume concentration, Reynolds number, magnetic field strength, and inclination angle on forced convection of nanofluids flow in a branching channel. Results obtained showed that Nusselt number increased with the increase of volume concentration and magnetic field strength. More numerical work by Hajiyan et al.\(^10\) and found that heat transfer is enhanced with the presence of magnetic field when magnetic nanofluids was inside a square enclosure. Vafeas et al.\(^11\) studied the effects of applying different magnetic field and volume concentration, respectively on a laminar flow in a different curved cylindrical annular duct. They found that the velocity of the flow increased with the increase of magnetic field and volume concentration. Mousavi et al.\(^12\) investigation revealed that Nusselt number increased by about 40% with the increase of applied magnetic field strength in a helical tube. Hekmat and Ziarati\(^13\) studied the effect of constant and alternating magnetic flux density on heat transfer enhancement in mini/micro thermal systems using ferrofluids flow of constant Reynolds number (Re = 66). Results showed a considerable increase in heat transfer at higher values of both constant and alternating magnetic field. Selimfendigil and Öztöp\(^14\) used Galerkin weighted residual finite element method to investigate natural convection of nanofluid in an inclined cavity including a curved shaped conductive partition under the impact of inclined magnetic field. Several parameters were used in this investigation such as Rayleigh number inclination angle of the cavity, Hartmann number, angle of the magnetic field, curvatures of the conductive partition, conductivity ratio, and volume fraction. Results showed that Nusselt number increased with the increase of Rayleigh number, volume fraction whereas it was reduced with higher values of Hartmann number. Also, a decrease in Nusselt number was observed when the radii of the vertical and horizontal elliptic curved partitions were increased. Siddiqui and Sheikholeslami\(^15\) used a TiO\(_2\)-water based nanofluid flow in a channel bounded by two porous plates to investigate analytically the effect of an oblique magnetic field. They found that by increasing volume fraction of the TiO\(_2\) nanoparticles, magnetic field intensity and angle, the fluid speed decreases, and the temperature increases, respectively. Temperature increase means that heat transfer increases and Nusselt number enhanced.
Fadaei et al.\textsuperscript{16} investigated the effects of magnetic field intensity, and the type of magnetic field source (i.e., a permanent magnet or current-carrying wire) on the forced-convection heat transfer of magnetic nanofluids in a constant heated pipe. It was found that by applying the magnetic field, Nusselt number increased, and it increased by 196\% under the application of permanent magnetic field of $3 \times 10^5 \text{A/m}$ for each one. Al Kalbani et al.\textsuperscript{17} used different types of nanofluids in a square enclosure under the application of magnetic field to study numerically the heat transfer and fluid flow of natural convection. It was found that heat transfer is enhanced with the increase in the concentration of volume fraction of nanofluids. However, a reduction in heat transfer was observed as Hartmann number decreased. Asfer et al.\textsuperscript{18} used a ferrofluid flowing in a heated circular stainless-steel tube to investigate the presence of magnetic field on the convective heat transfer characteristics. Results showed that there is no enhancement in laminar convective heat transfer for ferrofluid as compared to its base fluid in the absence of magnetic field. Also, Nusselt number increased with an increase in the magnetic field gradient. This was observed when they used double-inline arrangement of magnets.

Based on the previous work in the open literature, it was concluded that most of the researcher’s work was on studying and investigating the effect of magnetic field strength on heat transfer enhancement of laminar flow nanofluids. However, experimental research studies on forced convective heat transfer with turbulent flow was in heated pipes with constant heating flux in the presence of magnetic field. Therefore, the research in this paper has been carried out using magnetite $\text{Fe}_3\text{O}_4$/water based nanofluids as the working fluid to investigate experimentally the effect of magnetic field strength on heat transfer enhancement of different turbulent flow of $\text{Fe}_3\text{O}_4$/water nanofluids and with different concentrations in a pipe heated with constant heat flux intensity.

**Proposed experimental setup**

**Experimental rig**

The proposed experimental rig setup is depicted in Figure 1. As shown, the experimental system consists of test section (insulated copper pipe), centrifugal pump, pipe lines, air coolant heat exchanger, storage tank with stirrer, electromagnet, data acquisition system, and personal computer. The storage tank of 15 L capacity is made of glass to store the $\text{Fe}_3\text{O}_4$ nanofluid mixture and is constantly stirred during experiment time so that all points in the tank becomes equal in temperature. Moreover, the used mixer ensures nanofluid stability during the test. The air cooled heat exchanger is used to keep the $\text{Fe}_3\text{O}_4$ nanofluid at the inlet test section at constant temperature. The $\text{Fe}_3\text{O}_4$ nanofluid is forced through the test section with an aid of a circulating centrifugal pump of 0.5 Hp through a flow meter of 10–80 L/min range capacity. The suction side of the copper pipe is connected to a storage tank. The flow rate of the $\text{Fe}_3\text{O}_4$ nanofluid is controlled with a bypass valve arrangement, and the required quantity of fluid is allowed into the test section through a flow meter as shown in Figure 2. The test section is a straight copper pipe of the inner diameter of 1.1 cm, outer diameter 1.27 cm, and length 120 cm. The copper pipe is heated uniformly by chrome heater of 20 mm gauge diameter and 420 W rating power so that the entire test section is subjected to constant heat flux boundary condition. The test section is insulated with rock wool insulation of thermal conductivity 0.040 W/m2 K, thickness 4 cm, and density 12 kg/m3 in order to minimize the heat loss from the test section to the surrounding. The hydrodynamic entry section is long enough to accomplish a fully developed flow at the entrance of the heat transfer test section. Two K-type thermocouples were mounted on the surface of the pipe at the inlet and outlet surfaces to measure the surface temperatures of the pipe and two K-type thermocouples were located at the inlet and exit of the test section to measure the working fluid ($\text{Fe}_3\text{O}_4$ nanofluid) inlet and outlet temperatures as shown in Figure 2. The K-type thermocouples are calibrated before fixing them at the specified locations. U-tube manometer with mercury as manometer liquid is provided for measuring the pressure drop across the test section. Electro-magnetic field is applied perpendicular to the flow direction near the inlet testing section and can be changed by altering the AC current supply to the magnet measured by a digital multimeter. Three values of magnetic field (15.1, 30.3, 45.35 mT) were used. These values were selected based on the work by Goharkkhah et al.\textsuperscript{19}
Preparation of Fe$_3$O$_4$/water nanofluids

For a synthesis of nanoscale Fe$_3$O$_4$, 8 g of ferrous chloride tetrahydrate (FeCl$_2$.4H$_2$O) in 150 mL of acidic deoxygenated distilled water and 16 g of ferric chloride hexahydrate (FeCl$_3$.6H$_2$O) in 200 mL acidic deoxygenated distilled water were dissolved separately. The ferrous chloride solution has been added gradually to the ferric chloride solution in a flask reactor with three open necks under vigorous stirring and in presence of N$_2$ gas at 70°C conditions as shown in Figure 3. After stirring for 30 min, black nanoparticles start precipitation. The stirring process was continued for two hours to reach solution pH = 9 using NH$_4$OH. The precipitates were separated by filter paper and washed several times with distilled water and ethanol until pH is neutral. Finally, the obtained magnetite nanoparticles were dissolved in 1 L volume of distilled water used as the base fluid. The nanofluid was dispersed using an ultrasonic processor (UP 200S, Hielscher Company, Germany) at 100% amplitude and 0.5 cycles for 15 min. In addition, the pH of nanofluid was adjusted at 9 pH value using NH$_4$OH. This procedure was repeated 10 times in order to prepare 10 L ferro-nanofluid. Moreover, ethanol was used as a surfactant. The authors ensured adequate dispersion of the magnetite nanoparticles in water by monitoring the magnetite nano-fluid stability on the shelf. It was stable for several days due to the strong repulsive forces between the nanoparticles. Three volume fraction 1.2%, 0.6%, 0.3% were prepared using the procedure above.

The samples were analyzed for physical properties (particle size distribution and morphology). Analytical analysis was performed included X-ray diffraction (XRD) using Cu K$_\alpha$ radiation source by Shimadzu X-ray diffractometer (XRD-6000). Scanning Electron Microscope (SEM) images were captured using (SEM, FEI company – Inspect F50/FE (Schottky Field Gun) high vacuum (6e$^{-4}$ Pa Everhart-Thornley SE detector Solid-State BSED)). Also, viscosity was determined via (Brookfield Viscometer, USA), as well as nanofluid density measured using pycnometric method. Results of nano-magnetite XRD showed that the XRD pattern revealed that the produced nanopowder is magnetite as shown in Figure 4. Six typical peaks at 30°, 35.4°, 43.3°, 53.7°, 57°, 63° were matched with the following crystal faces of pure magnetite (220), (311), (400), (422), (511), and (440), respectively. Based on Scherrer equation, the mean particles size was equal (10.3 nm).

Based on Alexander and Klug, the crystallite size can be computed as:

$$L = \frac{k \times \lambda}{\beta \times \cos \theta}$$  

where:

$K$ is a constant commonly equal to 0.9, $\lambda$ is the X-ray wavelength 1.5418 Å.
\( \beta \) is the width at half the maximum intensity, in radians = 0.8131 \( \times \pi / 180 \).

\( \theta \) is the Bragg angle (in degrees) = 35.4/2 = 17.7.

The mean particles size \( L \) can be computed and equal to 10.3 nm. The Scanning electron microscope (SEM) image as shown in Figure 5 revealed that the magnetite powder particle size is within the nano range around 10nm with spherical shape.

**Theory of work**

**Heat transfer governing equation**

Convective heat transfer coefficient of fluid. The specific constant heating flux \( q_{\text{heat}} \) supplied to the test section by the rated heating chrome element is calculated as follows:

\[
q_{\text{heat}} = \frac{Q_{\text{heat}}}{A_S} = \frac{IV}{\pi DL}
\]  

Where:

\( Q_{\text{heat}} \): heating rate, \( q_{\text{heat}} \): heat flux, \( A_S \): surface area, \( I \): measured current, \( V \): measured voltage, \( D \): pipe diameter, and \( L \): heating length of the pipe.
The convective heat transfer by coolant is given as:

$$\dot{Q}_{\text{conv}} = \rho \dot{Q}_{\text{flow}} C_p (T_{f,\text{out}} - T_{f,\text{in}})$$  \hspace{1cm} (3)

Where $\dot{Q}_{\text{conv}}$: convective heat transfer, $\dot{Q}_{\text{flow}}$: flow rate, $T_{f,\text{out}}$, $T_{f,\text{in}}$ are the temperatures of outlet and inlet fluid flow, respectively.

The convective heat transfer coefficient along the heating section of the pipe is given by:

$$h = \frac{q_{\text{heat}}}{(T_{S,\text{avg}} - T_{f,\text{avg}})}$$  \hspace{1cm} (4)

Where $h$: convective heat transfer coefficient $W/m^2\cdot K$, $T_{S,\text{avg}}$, $T_{f,\text{avg}}$ are the average pipe surface and fluid temperatures, respectively.

Combining (2), (3), (4) to give an expression for convective heat transfer coefficient

$$h = \frac{\rho \dot{Q}_{\text{flow}} C_p}{\pi DL} \times \frac{(T_{f,\text{out}} - T_{f,\text{in}})}{(T_{S,\text{avg}} - T_{f,\text{avg}})}$$  \hspace{1cm} (5)

Nusselt number. Nusselt number is given by$^{21}$ as follows:

$$Nu = \frac{hD}{k_{\text{eff}}}$$  \hspace{1cm} (6)

Where $k_{\text{eff}}$: effective thermal conductivity of the fluid.

Thermal performance factor. Thermal performance factor (TPF) which represents the ratio of the relative effect of change in heat transfer rate represented by Nusselt number to change in friction factor. It is defined in equation (7)$^{22}$

$$TPF = \frac{Nu_{\text{nf}}/Nu_{\text{bf}}}{(f_{\text{nf}}/f_{\text{bf}})^{1/3}}$$  \hspace{1cm} (7)

Where, subscripts $\text{nf}$ and $\text{bf}$ represent nanofluid and base fluid, respectively

Governing equations of nanofluid properties

Volume fraction of nanoparticles. The volume fraction of nanofluid is expressed as:

$$\varphi = \frac{m_{\text{np}}}{0.001 \rho_{\text{np}}} = \frac{\rho_{\text{nf}} - \rho_{\text{bf}}}{\rho_{\text{np}} - \rho_{\text{bf}}}$$  \hspace{1cm} (8)

$$V_{\text{np}} = \varphi V_T$$  \hspace{1cm} (9)

Where $V_{\text{np}}$: volume of nanoparticles and $V_T$: total volume of base fluid.

Effective thermal conductivity of nanofluid. Based on effective medium theory EMT, randomly dispersed, and uniformly sized spherical particles, Das et al.$^{23}$ reported that Maxwell investigated the conduction analytically through a suspension particle and showed that the effective thermal conductivity of nanofluid can be calculated as:

$$k_{n,\text{eff}} = k_{nf} \times \left( \frac{(k_{bf} - k_{nf}) + 2\varphi (k_{np} - k_{nf})}{(k_{bf} + 2k_{nf}) - \varphi (k_{bf} - k_{nf})} \right)$$  \hspace{1cm} (10)

Where, $k_{n,\text{eff}}$: effective thermal conductivity of nanofluid, $k_{bf}$: thermal conductivity of based fluid, $k_{nf}$: thermal conductivity of nanofluid, and $\varphi$: particle-volume concentration.

Density of nanofluid. The density of a nanofluid is based on the classical theory of two-phase mixture given in Deiss et al.$^{24}$ Behzadmehr et al.$^{25}$

$$\rho_{\text{nf}} = (1 - \varphi) \rho_{\text{bf}} + \varphi \rho_{\text{np}}$$  \hspace{1cm} (11)

Where $\rho_{\text{nf}}$: density of nanofluid, $\rho_{\text{bf}}$: density of base fluid, $\varphi$: volume fraction of nanoparticles, and $\rho_{\text{np}}$: density of nanoparticles.

Specific heat capacity of nanofluid. The following equation is proposed for determining specific heat capacity of nanofluid and assessing heat transfer performance of nanofluids$^{26,27}$

$$C_{p,\text{nf}} = (1 - \varphi) C_{p,\text{bf}} + \varphi C_{p,\text{np}}$$  \hspace{1cm} (12)

Where, $C_{p,\text{nf}}$: specific heat capacity of nanofluid, $C_{p,\text{bf}}$: specific heat capacity of base fluid, and $C_{p,\text{np}}$: specific heat capacity of nanoparticles.

Dynamic viscosity of nanofluid. The dynamic viscosity of nanofluid can be computed as follows:

$$\mu_{\text{nf}} = (1 + 2.5\varphi) \times \mu_{\text{bf}}$$  \hspace{1cm} (13)

Where, $\mu_{\text{nf}}$: dynamic viscosity of nanofluid and $\mu_{\text{bf}}$: dynamic viscosity of base fluid.

Governing equations of fluid flow

Mean velocity. The mean velocity of nanofluid can be computed as follows:

$$u = \frac{\dot{Q}_{\text{flow}}}{C}$$  \hspace{1cm} (14)

Where $\dot{Q}_{\text{flow}}$: flow rate, $C$: cross sectional area of the pipe

Reynolds number. Reynolds number is calculated based on pipe diameter as follows:
\[
\text{Re} = \frac{\rho u D}{\mu}
\]  
(15)

Where \(\rho\): density of fluid flow, \(u\): velocity of fluid flow, and \(D\): pipe diameter.

**Pressure drop differential.** Pressure drop in the pipe can be determined as follows:
\[
\Delta p = \rho g \Delta H
\]  
(16)

Where \(\Delta H\): pressure differential height (mmHg).

**Electromagnetic field strength.** The electro-magnetic field strength is calculated as follows:
\[
\Phi = \frac{\mu I}{2\pi r}
\]  
(17)

Where \(\Phi\): magnetic field strength, \(\mu\): permeability of medium \((H/m)\), and \(r\) is the radius of the pipe.

**Experimental procedure**

The main objectives of this current work is to investigate experimentally heat transfer enhancement using water and Ferro-nanofluids \((\text{Fe}_3\text{O}_4/\text{water})\) in a constant heated pipe under the application of magnetic field by varying the following parameters:

- Flow rates ranging from 1000 to 6000 mL/min.
- Different values of magnetic field strength \((15.1, 30.3, 45.5 \text{ mT})\).
- Different values of nanofluids concentration by weight \((0.3, 0.6, 0.3\%)\).

The experiments have been conducted using various volume flow rates of water and ranging from 1000 to 4200 mL/min. Three different concentrations of \(\text{Fe}_3\text{O}_4\) nanofluids \(\varphi = 1.2\%, 0.6\%, 0.3\%\) were used, and three different magnetic field intensity of 15.1, 30.3, 45.5 mT were applied. Prior to any experimental work, the measurement tools such as thermocouples, flowmeter, solar meter, and digital multimeters were calibrated regularly during the experimental work to make sure that all the measurements are within the tools accuracy, moreover, to improve the accuracy and precision, multiple measurements were recorded. Also, in order to avoid any agglomeration of the nanoparticles and ensure that all of the experiments have been carried out at equal conditions, the ferrofluid samples have been ultrasonicated before each experiment.

For each flow rate, the required measurements for all experiments are; volume flow rate considered \(Q_{\text{flow}}\), seven readings were recorded; these are, pipe surface inlet and outlet temperatures \(T_{\text{S,in}}, T_{\text{S,out}}\), flow inlet and outlet temperatures \(T_{f,\text{in}}, T_{f,\text{out}}\), manometer differential readings, and current and voltage \(I, V\) reading for the electromagnetic field strength values considered \((15.1, 30.3, 45.5 \text{ mT})\). The descriptions of the experimental work are presented hereafter. It should be noted that based on the literature review, the saturation magnetization of the magnetite nano particles is in the range of 49–70 emu/g \(^{28,29}\). In addition, it was found that the specific absorption rate decreases with the increase of nano-particle concentration. The specific absorption rate obtained for magnetite nano-particle increases almost linearly with the field frequency and nonlinearly with the field strength \(^{30}\).

**Water as the working fluid**

The first experiment was conducted using water as the flowing fluid through a heated copper pipe under constant heat flux of 420 W. Enough time was given to the system to reach the steady state conditions. Different flow rates \((1000, 2000, 3000, 3800, 4200 \text{ mL/min})\) were used and the required measurements values aforementioned in Section 4 were recorded.

**\(\text{Fe}_3\text{O}_4\) ferro-nanofluid of concentration (0.3, 0.6, and 0.3 wt\%) as the working fluid**

Applying the same procedure as in Section 4.1, several experiments were carried out using \(\text{Fe}_3\text{O}_4\) nanofluid without the presence of magnetic field, and in the presence of different magnetic field intensity \((15.1, 30.3, 45.5 \text{ mT})\), respectively. Same measurements were recorded as in Section 4.1 were recorded.

**Results and discussions**

**Properties of \(\text{Fe}_3\text{O}_4\) nanofluids**

In order to determine the properties of \(\text{Fe}_3\text{O}_4\) nanofluids used in the experimental work, the volume concentration of nanoparticles \(\varphi\), effective thermal conductivity of nanofluid \(k_{\text{nf,eff}}\), density \(\rho_{\text{nf}}\), specific heat capacity \(C_{p,\text{nf}}\), and dynamic viscosity \(\mu_{\text{nf}}\) of nanofluid are calculated using equations (8)–(13), respectively. The results of calculation of aforementioned properties \(\text{Fe}_3\text{O}_4\) nanofluid concentration by weight \((0.3, 0.6, 1.2\%)\) are tabulated in Table 1.

**Fluid flow and heat transfer characteristics determination of water and \(\text{Fe}_3\text{O}_4\) nanofluids**

In order to determine the fluid flow properties of water and \(\text{Fe}_3\text{O}_4\) nanofluids in the studied range of fluid flow rates, volume concentration by weight wt\%, the fluid velocity \(u\), Reynolds number \(\text{Re}\), pressure drop in the heated pipe, the convective heat transfer \(Q_{\text{conv}}\), thermal...
heat transfer coefficient $h$, and Nusselt number $Nu$ are all calculated based on the equations presented in Section 3 for water and Fe$_3$O$_4$ nanofluids. These are obtained in the absence and in the presence of different magnetic field strength ($F = 0$, $15$, $30$, $45$) mT, respectively.

**Pressure drop characteristics**

**Effect of magnetic field strength on pressure drop.** Pressure drop is an important parameter to consider in the application of nanofluids in a heat exchanging equipment. Figure 6(a) and (b) illustrates the variation of pressure drop as a function of Reynolds number for water and Fe$_3$O$_4$ nanofluids in the absence and presence of magnetic field strengths ($F = 0$, $15$, $30$, $45$) mT at the specified concentrations of 0.6, 1.2 wt%, respectively. In general, pressure drop across the pipe is produced drag forces exerted on the flow field, turbulence augmentation, and rotational flow as reported by Aghabozorg et al.31 It can be observed from Figure 6(a) and (b) that a greater Reynolds number corresponds to a greater amount of pressure drop for both water and Fe$_3$O$_4$ nanofluids, respectively. However, this event occurs more severely at higher values and of Reynolds number. This is may be due to the effect of flow velocity increase and this results in turbulence augmentation.32 Also, pressure drop values continue to increase with the rise of magnetic field strength. This can be explained as in the existence of external magnetic field, the magnetic particles suspended in the base fluid tends to remain chained-alignment in the direction of magnetic field. This increases the Fe$_3$O$_4$ nanofluid viscosity and consequently the pressure drop.19,33 In addition to, high values of pressure drop are obtained at magnetic field strength equal to ($F = 45.5$) mT.

**Effect of Fe$_3$O$_4$ nanofluid concentration on pressure drop.** To show clearly the effect of Fe$_3$O$_4$ nanofluid concentrations (0.3, 0.6, 1.2 wt%) on pressure drop, Figure 7 is plotted as a function of Reynolds number at a specified magnetic field strength ($F = 45.5$) mT. It is clearly noticed that pressure drop increases with Fe$_3$O$_4$ nanofluids concentration, this is due to the increase of viscosity of the nanofluids.19 Also, a sharp rise in pressure drop is obtained at high values of Reynolds number and the highest pressure drop is observed at ferro-nanofluid concentration 1.2 wt% as compared to the

**Table 1.** Properties of Fe$_3$O$_4$ nanofluid of concentrations by weight $\varphi = 1.2, 0.6, 0.3$ wt%.

| Properties of Fe$_3$O$_4$ nanofluid | Calculated Values |
|-----------------------------------|-------------------|
|                                   | Volume concentration of nanoparticles by weight, $\varphi$ |
|                                   | 1.2%wt | 0.6%wt | 0.3%wt |
| Effective thermal conductivity of nanofluid, $k_{\text{eff}}$ | 0.5854W/m.K | 0.5830W/m.K | 0.5823W/m.K |
| Density, $\rho_{\text{nf}}$ | 1045kg/m$^3$ | 1036.7kg/m$^3$ | 1010.76kg/m$^3$ |
| Specific heat capacity, $C_p,_{\text{nf}}$ | 4045.5J/kgK | 4053.55J/kgK | 4075.02J/kgK |
| Dynamic viscosity, $\mu_{\text{nf}}$ | 0.000942NS/m$^2$ | 0.000548NS/m$^2$ | 0.000923NS/m$^2$ |

![Figure 6](image-url)
other two concentrations (0.3, 0.6 wt%), respectively. Furthermore, water fluid showed the lowest pressure drop compared with the ferrofluids. This confirmed that the viscosity tends to increase the pressure drop.

**Heat transfer characteristics**

*Effect of magnetic field strength on heat transfer coefficient.* Figure 8(a) to (c) show the variation of heat transfer coefficient with Reynolds number for water and Fe3O4 nanofluids at magnetic field strength (Φ = 0, 15.1, 30.3, 45.5) mT for a specific Fe3O4 nanofluids concentration by weight. Initial observation from Figure 8(a) to (c) show that the curves have similar trends in which heat transfer coefficient increases with the increasing of Reynolds number. This is due to the increase in velocity flow. Also, heat transfer coefficient improved with the rise of magnetic field strength. This may be attributed to the improvement of the thermophysical properties of ferrofluids under the influence of magnetic field. Similar results were obtained by other
researchers. Furthermore, it is found that the average rise in heat transfer coefficient over the studied range of Reynolds number is 9.4%, 26.1%, 31.3% under the applied magnetic field strength $F = (15, 30, 45)\, \text{mT}$, respectively compared to the absence of magnetic field strength $F = (0)\, \text{mT}$.

**Effect of Fe$_3$O$_4$ nanofluid concentration on heat transfer coefficient.** Figure 9(a) to (d) are plotted to show the variation of Nusselt number with Reynolds number for different concentration by weight (0.3, 0.6, 1.2 wt%) at a specified magnetic field strength $\Phi = (15.1, 30.3, 45.5)\, \text{mT}$, respectively compared to the absence of magnetic field strength $\Phi = (0)\, \text{mT}$.

**Nusselt number characteristics.**

**Effect of magnetic field strength on Nusselt number.** In order to study the effect of magnetic field strength variation ($\Phi = 0, 15.1, 30.3, 45.5)\, \text{mT}$ on heat transfer enhancement. Nusselt number was plotted against Reynolds number for water and at a specified Fe$_3$O$_4$ nanofluid concentration by weight (0.3, 0.6, 1.2 wt%), respectively, as shown in Figure 10(a) to (c). It can be observed that heat transfer rate represented by Nusselt number shows similar trends and increases with the increasing magnetic field strength at each constant concentration. Also, it is noticed that there is a high rise in Nusselt number in the presence of magnetic field compared to the absence of magnetic field and base fluid water, respectively.
This may be due to the chain-like structures formed in applied magnetic fields, which caused the convective heat transfer coefficient increased, and consequently Nusselt number $\text{Nu}$. In the presence of applied magnetic field, magnetic moments had the tendency to align with the applied magnetic field. When the magnetic force rather than the thermal motion exerted a major influence on magnetic nanoparticles, the nanoparticles adhered together and formed chains oriented along the direction of the applied field. Thus, the chains connected the nanofluids flow and the pipe wall acting as thermal passages which leads to an enhancement in heat transfer. The average Nusselt number enhancement of 8.8%, 13.1%, and 23.9% is obtained in the presence of magnetic field strength ($\Phi = 0, 15.5, 30.3, 45.5 \text{ mT}$), in the studied range of Reynolds number, compared to the absence of magnetic field ($\Phi = 0 \text{ mT}$). Finally, the heat transfer enhancement, and consequently Nusselt number by the increment of Reynolds number may be due to the better confounding of fluid layers as a result of an increase in velocity in higher Reynolds number.

Figure 10. (a) Variation of Nusselt number with Reynolds number for different magnetic field strength ($\Phi = 0, 15.5, 30.3, 45.5 \text{ mT}$) at a specified Fe$_3$O$_4$ nanofluid concentration 0.3 wt%. (b) Variation of Nusselt number with Reynolds number for different magnetic field strength ($\Phi = 0, 15.5, 30.3, 45.5 \text{ mT}$) at a specified Fe$_3$O$_4$ nanofluid concentration 0.6 wt%. (c) Variation of Nusselt number with Reynolds number for different magnetic field strength ($\Phi = 0, 15.5, 30.3, 45.5 \text{ mT}$) at a specified Fe$_3$O$_4$ nanofluid concentration 1.2 wt%.

Effect of Fe$_3$O$_4$ nanofluid concentration on Nusselt number. To study the effect of Fe$_3$O$_4$ Nano-fluids concentration by weight (0.3, 0.6, 1.2 wt%) on Nusselt Number at different Reynolds Number at a specified magnetic field strength ($\Phi = 0, 15.5, 30.3, 45.5 \text{ mT}$), Figure 11(a) to (d) are drawn and it was found, in general, that all figures show similar trends as Nusselt number increases with the increase of Reynolds number and nanofluid concentration. The best values for Nusselt number was obtained for concentration (1.2 wt%) and magnetic field strength (45.5 mT), respectively for the Reynolds number range considered in this work. This can be due to the fact that Nusselt number is directly proportional to heat transfer coefficient which itself is directly proportional to the thermal conductivity of the nanofluids and inversely proportional to the thickness of thermal boundary layer. Therefore, a possible reason for the increase in heat transfer is believed to be the nanoparticles presented in the base fluid which increase the thermal conductivity, delay and disturb the thermal boundary layer, and
accelerate the energy exchange process in the fluid due to chaotic movement of the nanoparticle.\(^{40,41}\) Again this can be attributed to the fact that higher concentration resulted in higher values of thermal conductivity of the nanofluid. Also, thermal heat transfer coefficient increased with the increase of magnetic field strength and this lead to higher Nusselt number.

**Thermal performance factor characteristics.** The combined effect of Nusselt number and friction factor is employed to assess the overall hydrothermal behavior of the nanofluids in the heated pipe using performance evaluation criterion as expressed in equation (7).

**Effect of \(\text{Fe}_3\text{O}_4\) nanofluids concentration on thermal performance factor.** Figure 12(a) to (d) show the variation of thermal performance factor as a function of Reynolds number for various concentration of ferrofluids by weight (0.3, 0.6, 1.2 wt%) at a specified magnetic field strength \((\Phi = 0, 15.5, 30.3, 45.5)\text{ mT}\), respectively. It can be observed that the performance factor increases with the increase in concentration and velocity flow. When Nusselt number enhancement is higher than friction changes, the performance factor is above unity which indicates the applicability of the heated pipe in the improvement of heat transfer. Based on that, it can be deduced from Figure 12(a) to (d) that ferrofluid of concentration 1.2 wt% produces the best heat transfer enhancement with relatively high values of thermal performance factor compared to other concentration 0.3, 0.6 wt%, respectively. This is due to high values of heat transfer coefficient and Nusselt number at concentration 1.2 wt% as discussed previously.

**Effect of magnetic field strength on thermal performance factor.** Figure 13 show the variation of thermal performance factor with Reynolds number for different magnetic field strength \((\Phi = 0, 15.5, 30.3, 45.5)\text{ mT}\) at a specified \(\text{Fe}_3\text{O}_4\) nanofluid concentration 0.6 wt%. Even though the effect of different magnetic field strength on thermal performance factor can be deduced from Figure 12(a) to (d). It would be useful to show this effect clearly by plotting Figure 13 which show the

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**Figure 11.** (a) Variation of Nusselt number with Reynolds number for \(\text{Fe}_3\text{O}_4\) nanofluids concentration by weight (0.3, 0.6, 1.2 wt%) at magnetic field strength \((\Phi = 0)\text{ mT}\). (b) Variation of Nusselt number with Reynolds number for \(\text{Fe}_3\text{O}_4\) nanofluids concentration by weight (0.3, 0.6, 1.2 wt%) at magnetic field strength \((\Phi = 15.5)\text{ mT}\). (c) Variation of Nusselt number with Reynolds number for \(\text{Fe}_3\text{O}_4\) nanofluids concentration by weight (0.3, 0.6, 1.2 wt%) at magnetic field strength \((\Phi = 30.3)\text{ mT}\). (d) Variation of Nusselt number with Reynolds number for \(\text{Fe}_3\text{O}_4\) nanofluids concentration by weight (0.3, 0.6, 1.2 wt%) at magnetic field strength \((\Phi = 45.5)\text{ mT}\).
variation of thermal performance factor for different magnetic field at constant concentration 0.6 wt%. It can be seen clearly that the thermal performance factor increases with the increase of magnetic field strength and Reynolds number, and most values are above unity. This means again that the heat transfer and Nusselt number are higher than friction factor which indicates the applicability of the heated pipe in the improvement of heat transfer.

**Uncertainty Analysis**

In order to assess the reliability of the experimental facility, the uncertainties of the experimental data are determined. The work calculation of the data uncertainties are based on the work.\(^{42-44}\) If \(x\) is a function of \(n\) independent variables, then the uncertainty in \(x\), which is written as \(U_x\), is given by

\[
U_x = \pm \sqrt{\sum_{i=1}^{n} \left( \frac{\partial x}{\partial y_i} \right)^2 (U_{y_i})^2}
\]

(18)

\[
\frac{U_x}{x} = \pm \sqrt{\sum_{i=1}^{n} \left( \frac{U_{y_i}}{y_i} \right)^2}
\]

(19)
Table 2. Variables uncertainties based on the instruments specifications.

| Instrument                               | Range of instrument | Uncertainty (\(U_x\)) | Values measured in experiment (°C) | Uncertainty (°C) |
|------------------------------------------|---------------------|------------------------|-------------------------------------|------------------|
| Thermocouples for surface temperature    | 0 – 200°C           | \(\sqrt{0.1^2 + 0.1^2} = 0.1414\) | 28.52°C – 44.95°C                  | 0.0031°C – 0.0049°C |
| Thermocouples for fluid temperature      | 0 – 200°C           | \(\sqrt{0.1^2 + 0.1^2} = 0.1414\) | 22.50°C – 32.58°C                  | 0.0043°C – 0.0063°C |
| Voltage (V)                              | 0 – 240 V           | 1                      | 0.0045 – 0.0045                    | 0.0045 – 0.0045   |
| Current (A)                              | 0 – 20 A            | 0.01                   | 0.0052 – 0.0052                    | 0.0052 – 0.0052   |
| Flow meter                               | 0 – 20 LPM          | 0.01                   | 1.0 – 6.0                          | 0.0100 – 0.0017   |
| U-tube manometer                         | 0 – 180 cmHg        | 0.1                    | 7.21 – 30.25                       | 0.0033 – 0.0014   |

Table 3. Uncertainty of physical quantities.

| Parameter                      | Maximum uncertainty | Minimum uncertainty |
|--------------------------------|---------------------|---------------------|
| Heat flux \(q_{heat} = \frac{Q_{heat}}{A_x} = \frac{IV}{\pi dL}\) | \(\frac{U_q}{q} = \sqrt{\left(\frac{U_V}{V}\right)^2 + \left(\frac{U_I}{I}\right)^2}\) | \(\frac{U_q}{q} = \sqrt{\left(\frac{U_V}{V}\right)^2 + \left(\frac{U_I}{I}\right)^2}\) |
| Heat transfer coefficient \(h = \frac{q_{heat}}{(T_{t,eq} - T_{r,eq})}\) | \(\frac{U_h}{h} = \sqrt{\left(\frac{U_V}{V}\right)^2 + \left(\frac{U_{T_{t,eq}}}{T_{t,eq}}\right)^2 + \left(\frac{U_{T_{r,eq}}}{T_{r,eq}}\right)^2}\) | \(\frac{U_h}{h} = \sqrt{\left(\frac{U_V}{V}\right)^2 + \left(\frac{U_{T_{t,eq}}}{T_{t,eq}}\right)^2 + \left(\frac{U_{T_{r,eq}}}{T_{r,eq}}\right)^2}\) |
| Nusselt number \(Nu = \frac{\rho \beta S}{k_a}\) | \(\frac{U_{Nu}}{Nu} = \frac{\beta S}{k_a}\) | \(\frac{U_{Nu}}{Nu} = \frac{\beta S}{k_a}\) |
| Reynolds number \(Re = \frac{\rho d \nu}{\mu}\) | \(\frac{U_r}{Re} = \sqrt{\left(\frac{U_V}{V}\right)^2 + \left(\frac{U_d}{d}\right)^2 + \left(\frac{U_\nu}{\nu}\right)^2}\) | \(\frac{U_r}{Re} = \sqrt{\left(\frac{U_V}{V}\right)^2 + \left(\frac{U_d}{d}\right)^2 + \left(\frac{U_\nu}{\nu}\right)^2}\) |
| Pressure drop \(\Delta p = \rho g \Delta H\) | \(\frac{U_{\Delta p}}{\Delta p} = \sqrt{\left(\frac{U_\rho}{\rho}\right)^2 + \left(\frac{U_g}{g}\right)^2 + \left(\frac{U_{\Delta H}}{\Delta H}\right)^2}\) | \(\frac{U_{\Delta p}}{\Delta p} = \sqrt{\left(\frac{U_\rho}{\rho}\right)^2 + \left(\frac{U_g}{g}\right)^2 + \left(\frac{U_{\Delta H}}{\Delta H}\right)^2}\) |

Where \(U_{y_i}\) is the uncertainty in variable \(y_i\).

The instruments used in the experimental analysis and their accuracy are given in Table 2.

Based on equations (18) and (19), the maximum uncertainties of the heat flux, heat transfer coefficient, Nusselt number, Reynolds number, and pressure loss are calculated and the results are presented in Table 3.

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**Conclusion**

Experimental work using Fe₃O₄/water nanofluids to investigate the effect of magnetic field strength of turbulent flow on heat transfer enhancement, and consequently Nusselt number in a heated pipe with constant heating flux has been carried out. The experimental work used various concentration by weight (1.2, 0.6, 0.3 wt%) and various magnetic field strength (\(\Phi = 0, 15.5, 30.3, 45.5\) mT). Experimental results were analyzed and the following remarks are observed:

(a) The Nusselt number was enhanced in the presence of magnetic field strength (\(\Phi = 0, 15.5, 30.3, 45.5\) mT).
(b) Thermal transfer coefficient and consequently Nusselt number is effected intensively by the presence of magnetic field and increase with
the increasing of magnetic field strength. The average increase in heat transfer coefficient and Nusselt number are 9.4%, 26.1%, 31.3% and 8.8%, 13.1%, and 23.9% in the presence of magnetic field ($\Phi = 15.5, 30.3, 45.5)\text{mT}$ compared to the absence of magnetic field and base fluid water, respectively.

(c) Enhancement of the heat transfer coefficient of Fe$_3$O$_4$-water nanofluids in the heated pipe is due to the accumulation of nanoparticles in the direction of magnetic field applied, and these accumulated nanoparticles worked as heat passages in the pipe.

(d) Thermal transfer coefficient and consequently Nusselt number are enhanced with increasing in ferrofluid concentration. This is due to the increase in thermal conductivity of nanoparticles.

(e) Pressure drop increases with the increase of Reynolds number for water and Fe$_3$O$_4$ nanofluids, respectively, which may attributed to the increase in viscosity. Also, higher pressure drop values was noticed with the increase of magnetic field strength of Fe$_3$O$_4$ nanofluids.

(f) It is found that the performance factor is above unity in the presence and absence of magnetic field strength. This means that Nusselt number enhancement is higher than friction changes, which indicates the applicability of the heated pipe in the improvement of heat transfer.

(g) These results can be useful for enhancing heat transfer in many engineering applications such as heat exchangers, medical devices, and electronic devices.

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## Appendix

### Notations

#### Symbols

| Symbol | Description | Unit |
|--------|-------------|------|
| $A_S$  | Surface area of the heated pipe | $m^2$ |
| $A_C$  | Cross sectional area of the heated pipe | $m^2$ |
| $A_S$  | Surface area | $m^2$ |
| $C_p$  | Specific heat capacity | $J/kg.K$ |
| $C_p_{np}$ | Specific heat capacity of nanoparticles | $J/kg.K$ |
| $C_p_{nf}$ | Specific heat capacity of nanofluid | $J/kg.K$ |
| $C_p_{bf}$ | Specific heat of base fluid | $J/kg.K$ |
| $D$    | Diameter of the heated pipe | $m$ |
| $\Delta h$ | Pressure differential height | $mmHg$ |
| $I$    | Current | $A$ |
| $k_{eff}$ | Thermal conductivity of fluid | $W/m.K$ |
| $k_{n,eff}$ | Effective thermal conductivity of nanofluid | $W/m.K$ |
| $k_{np}$ | Thermal conductivity of nanoparticles | $W/m.K$ |
| $k_{nf}$ | Thermal conductivity of base fluid | $W/m.K$ |
| $L$    | Crystalline size | $nm$ |
| $m_{np}$ | Mass of nanoparticles | $kg$ |
| $\dot{Q}_{conv}$ | Convective heat transfer | $kJ/s$ |
| $q_{heat}$ | Specific constant heating flux | $kJ/m^2$ |
| $\dot{Q}_{flow}$ | Flow rate | $m^3/s$ |
| $Re$   | Reynolds number | $------$ |
| $r$    | Radius of heating pipe | $m$ |
| $T_{s,avg}$ | Average pipe surface temperature | $^\circ C$ |
| $T_{f,avg}$ | Average pipe fluid temperature | $^\circ C$ |
| $T_{f,in}$ | Inlet pipe fluid temperature | $^\circ C$ |
| $T_{f,out}$ | Outlet pipe fluid temperature | $^\circ C$ |
| $u_m$  | Mean velocity in the pipe | $m/s$ |
| $V_T$  | Total volume of base fluid | $m^3$ |
| $V_{np}$ | Volume of nanoparticles | $m^3$ |
| $V$    | Voltage | $Volt$ |

#### Greek letters

| Symbol | Description | Unit |
|--------|-------------|------|
| $\beta$ | Half the width of maximum intensity | $rad$ |
| $\theta$ | Bragg angle | $^\circ$ |
| $\phi$  | Volume fraction of nanofluid | $------$ |
| $\Phi$  | Magnetic field strength | $T$ |
| $\rho$  | Density | $kg/m^3$ |
| $\rho_{np}$ | Density of nanoparticles | $kg/m^3$ |
| $\rho_{nf}$ | Density of nanofluid | $kg/m^3$ |
| $\rho_{bf}$ | Density of base fluid | $kg/m^3$ |
| $\rho_{np}$ | Density of nanoparticles | $kg/m^3$ |
| $\mu_{nf}$ | Dynamic viscosity of nanofluid | $N.s/m^2$ |
| $\mu_{bf}$ | Dynamic viscosity of basefluid | $N.s/m^2$ |
| $\mu$   | Permeability of medium | $H/m$ |

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