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The Effect of Magnetic Field with Nanofluid on Heat Transfer in a Horizontal Pipe

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Abstract

This work presents an experimental study of heat transfer and flow of distilled water and metal oxide nanofluid Fe_3O_4-distilled water at concentrations of (φ = 0.3, 0.6, 0.9 %) by volume in a horizontal pipe with constant magnetic field. All the tests are carried out with Reynolds number range (2900-9820) and uniform heat flux (11262-19562 W/m^2). The results show that, the nanofluid concentration and magnetic intensity increase, the Nusselt number increases. The maximum enhancement in Nusselt number with magnetic nanofluid is (5.4 %, 26.4 %, 42.7 %) for volume concentration (0.3, 0.6, 0.9 %) respectively. The enhancement is maximized with magnetic intensity (0.1, 0.2, 0.3 tesla) respectively to (43.9, 44.3, 46 %) with volume concentration (0.9 %). The heat transfer enhancement decreases with the increasing of Reynold number with using magnets. The friction factor increases with nano volume concentration increase and the intensity of magnet and decreases with increase of Reynold number.

Keyword: *magnetic effect on nanofluid, heat transfer enhancement by nanofluid, turbulent flow in horizontal pipe.*

1. Introduction

Conventional fluids, such as water, lubricant, and ethylene glycol are normally used as heat transfer fluids. Solid particles as an additive suspended into the base fluid to enhancement heat transfer by change the properties of fluid. [1]. Sundar et al. [2] studied experimentally the convective heat transfer coefficient and friction factor characteristics of Fe_3O_4 Nanofluid added to water that, for flowed in a circular tube. The heat transfer coefficient was enhanced by 30.96 % and friction factor by 10.01 % at 0.6 % nano Fe_3O_4 volume concentration compared to flow of water at similar operating conditions. Jie et al. [3] studied experimentally the forced convective heat transfer properties of water with Fe_3O_4 Nanofluid. Ghofrani et al. [4] experimentally investigated on forced convection heat transfer of ferrofluid flow passing through a circular copper tube in the presence of an alternating magnetic field, a maximum enhancement was 27.6% in the convection heat transfer was observed. Nor et al. [5] studied numerically the turbulent (Fe_3O_4-water) flow in a square straight channel. Reynolds number range was from 10,000 to 50,000 and nanoparticle volume concentration was from 0 % to 2 %. Mohammad et al. [6] investigated numerically the forced convective heat transfer of water based Fe_3O_4 nanofluid (ferrofluid) in the presence of an alternating non-uniform magnetic field. Comparing the results with zero magnetic field case, the result showed that the heat transfer enhanced increases when the Reynolds number increased and reached a maximum of 13.9 % at Re=2000 and the maximum pressure drop increase of 6 % at Re=2000. Mohammad et al. [7] investigated experimentally and numerically the effect of a magnetic field on the fully developed forced convection of Fe_3O_4 flow inside a copper tube. The results show that the heat transfer increases with increase of alternating magnetic field frequency. Mehdi [8] evaluated theoretically the flow and heat transfer characteristics of the suspensions containing Fe_3O_4 magnetic nanoparticles in turbulent flow regime. Nusselt number was increased by raising the Reynolds number and mean concentration.

2. Nanofluid Preparation and Properties

The nanoparticles and the distilled water are mixed directly by mixer with (2400 rpm) for 20 minutes before each experiment, the concentrations used in the experiments are (φ = 0, 0.3, 0.6 and 0.9 % by volume). Volume of water used in the test rig is (5 L). The volume concentration is evaluated from the following relation in percentage:

$$\varphi = \frac{volume\ of\ nanopartical}{volume\ of\ nanopartical + volume\ of\ water} \times 100 \quad ...(1)$$

$$\varphi = \frac{(m/\rho)_{nanopartical}}{(m/\rho)_{nanopartical} + (m/\rho)_{water}} \times 100 \quad ...(2)$$

The properties of nanofluid (viscosity, specific heat and density) are measured experimentally and listed in Table (1) below

Table 1,
Experimental measurements for the properties of nanofluid.

	Distilled Water	**Fe_3O_4 (80 nm) – distilled water**		
Nanoparticles Concentration (vol. %)	0.0	0.3	0.6	0.9
Viscosity ($N.s/m^2$)	$5.96*10^{-4}$	$7.73*10^{-4}$	$8.345*10^{-4}$	$8.8869*10^{-4}$
Specific heat (kJ/kg.K)	4.1821	4.156	4.0864	4.0255
Density (kg/m^3)	990.1	1001.4	1001.8	1020.7
Thermal conductivity (W/m.K)	0.637	0.6426	0.6482	0.6539

For specific heat measurements:
The energy balance for water case:

$$Q_H = Q_V + Q_W \quad ...(3)$$

Energy balance in case of nanofluid takes the following form:

$$Q_H = Q_{nf} + Q_V \quad ...(4)$$

$$V\,I\,t = m_{nf}\, C_{nf}\, \Delta T + m_V\, C_V\, \Delta T \quad ...(5)$$

The thermal conductivity was estimated from the equation [9]

$$k_m = k_f \left[\frac{2+K_{pf}+2\emptyset(K_{pf}-1)}{2+K_{pf}-\emptyset(K_{pf}-1)}\right] \quad ...(6)$$

Where:

$$k_{pf} = \frac{k_p}{k_f} \quad ...(7)$$

3. Experimental Set Up and Procedure

The experimental rig consists of copper tube of inner and outer diameter (14, 15.8) mm with 1500 mm length, a helical heat exchanger Nanofluid tank, pumps, flow meters, thermorecorder, varic, electric board, magnets and fittings, as shown in Figure (1).

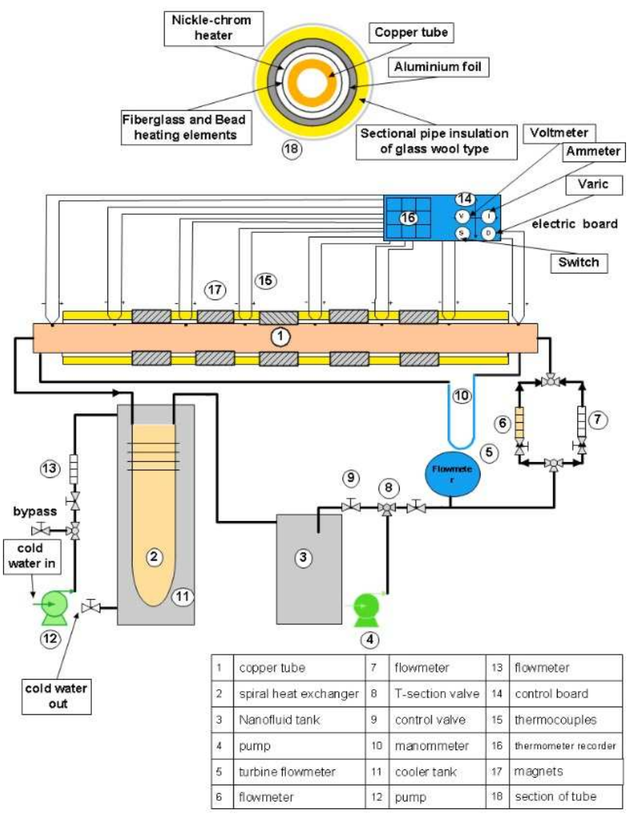


Fig.1. Schematic diagram of the experimental test rig.

The tube outer surface is electrically heated by a coil made from Nichrome material to generate constant heat flux (2000 W). An electric insulator of fiberglass is winded over the tube. Drilled ceramic bead elements are inserted around the wire heater to insulate the electrical heater and then the wire heater is winded around the pipe. An Aluminum foil and sectional pipe insulation glass wool type was used to insulate the test section. Eight thermocouples (k–type) were used to record the temperatures of variable locations of the test rig. Six thermocouples were used to measure the temperatures along the outer surface of test section. The thermocouples were located along the test section with a space distance of (22 cm) between each one. Two thermocouples were immersed in the flow stream to measure the inlet and outlet temperatures of the fluid in the test section. A stainless steel tank of (24 L) capacity was used to accumulate cold nanofluid from heat exchanger to feed the pump with the required amount of working fluid. Spiral heat exchanger was fabricated from a copper tube coil of (15 m) long and (12.5 cm) diameter used to cool the hot nanofluid came from the test section. The coil is placed in a stainless steel tank of (125 L) capacity filled with re-circulating water. U-tube manometer was used to record the pressure drop across the test section. Three types of magnets were used in this experimental work as presented in Table (2), where the strength at surface and center of pipe were measured by Gauss meter in Ministry of Science and Technology.

Table 2,
Strength of the three magnets.

No.	Type of magnet	Number of magnet used	Strength of magnet at surface (Gauss)	Strength at center of pipe (20 mm) (Gauss)
1	Ferrite	5	1000	600
2	Neodymium	20	2000	1200
3	Neodymium	10	3000	2220

The experiments were done (1) with distilled water (2) with nanofluid: (Fe_3O_4- distilled water) at concentrations (φ = 0. 3, 0.6 and 0.9 % by volume) (3) with magnetic field at each concentration used three intensities (0.1, 0.2 and 0.3 Tesla). All these tests were carried out under entrance region turbulent flow with Reynolds number range (2950-9820), flow rate (1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5 l/min) and uniform heat flux range (11114-19643 W/m^2).

4. Data Reduction

The power on the tube outer surface is given by:

$$P = V \times I \qquad ... (8)$$

The amount of the heat transferred from the heating wire to the nanofluid is given by:

$$Q_{nf} = \dot{m} \times C_{nf} \times (T_o - T_i) \qquad ... (9)$$

The heat balance between the nanofluid (Q_{nf}) and heat input (P) is found to be within 10 % for all runs, that is:

$$\eta = \frac{P - Q_{nf}}{P} < 10\ \% \qquad ... (10)$$

The heat flux is given by:

$$\dot{q} = \frac{Q_{nf}}{A_s} = \frac{Q_{nf}}{\pi D L} \qquad ... (11)$$

The local heat transfer coefficient is calculated as follows: [11]

1. Starting from the known values {$\dot{q}$, $T_{so}(x)$}
2. Using the conduction equation in the cylinder to calculate $T_{si}(x)$:

$$\dot{q} = \frac{Q_{nf}}{A_s} = \frac{2\pi k \Delta x [T_{so}(x) - T_{si}(x)]}{\pi D \Delta x \times \ln(\frac{r_o}{r_i})} = \frac{2k[T_{so}(x) - T_{si}(x)]}{D \times \ln(\frac{r_o}{r_i})} \qquad ... (12)$$

3. The mean bulk fluid temperature, $Tm(x)$ at the section (x):

$$dq = q^{"} p dx = \dot{m}\, C_{nf}\ dT_m \qquad ... (13)$$

Where $p = \pi D_i$ is the perimeters;

$$dT_m = \frac{q^{"} \pi D_i}{\dot{m}\, C_{nf}}\, dx \qquad ... (14)$$

The variation of T_m with respect to x is determined by integrating equation (13) from $x = 0$ to x and after simplifying using q'' term and $T_m(x=0) = T_i$, or

$$T_m(x) = T_i + \frac{(T_o - T_i)}{l}\, x \qquad ... (15)$$

Thus, the local heat transfer coefficient becomes:

$$h(x) = \frac{\dot{q}}{T_{si}(x) - T_m(x)} \qquad ... (16)$$

The local Nusselt Number is given by [2]:

$$Nu(x) = \frac{h_x D}{k_{nf}} \qquad ... (17)$$

The average value of Nusselt number in the thermal developing region can be expressed by:

$$Nu = \frac{1}{L}\int_0^L Nu\,(x)\,dx \qquad \dots(18)$$

The experimental values of Nusselt number are compared with the values estimated from: empirical correlation of Gnielinski's [2].

$$Nu = \frac{\left(\frac{f}{2}\right)(Re-1000)Pr}{1+12.7\left(\frac{f}{2}\right)^{0.5}\left(Pr^{\frac{3}{2}}-1\right)} \qquad \dots(19)$$

Where;

$f = (1.58 lnRe - 3.82)^{-2}$ for $2300 < Re < 5 \times 10^6$ and $0.5 < Pr < 2000$

Based on the practically measured pressure drop, friction factor can be calculated using Darcy equation, [12]:

$$f = \frac{2 \times \Delta p \times D}{L \times \rho \times u^2} \qquad \dots(20)$$

Where:

$$\Delta P = \gamma_{nf}\left(\frac{\rho_{CCl4}}{\rho_{nf}} - 1\right) \times H \qquad \dots(21)$$

H: head of manometer.

Experimental Procedure

The first set of experiments is done with distilled water, in order to validate the rig performance. The second set of experiments include the study of nanofluid: Iron Oxide ($Fe3O4$- distilled water) with concentrations (φ = 0. 3, 0.6 and 0.9 % by volume). The third set of experiments included the magnetic field with each concentration for three intensity (0.1, 0.2 and 0.3 Tesla).

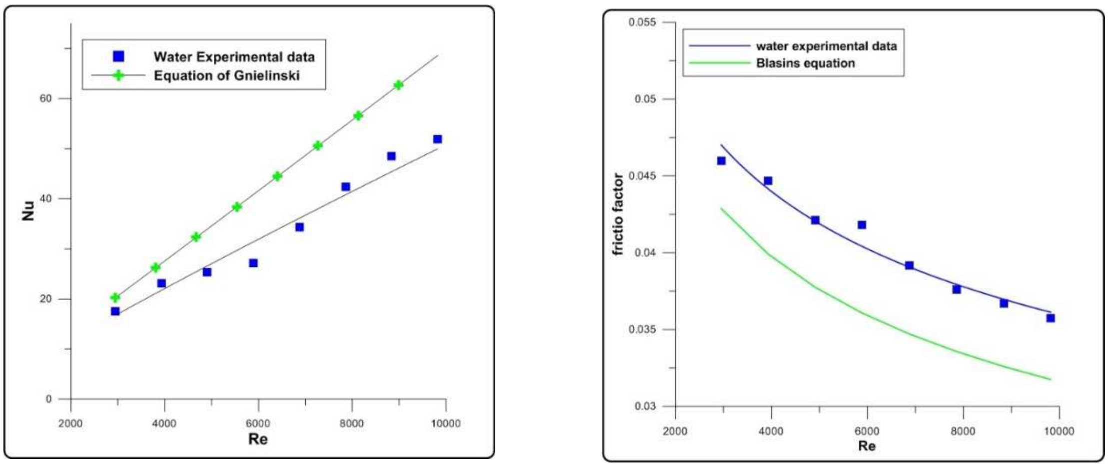
1. Preparation of nanofluid and put it in nanofluid tank.
2. Switch the pump to circulate the nanofluid in the test rig.
3. The flow rate is adjusted by means of the control valve and the balance valve to get the desired flow rate.
4. Switch on the electrical heater and adjusted to the desired heat flux by the regulating device.
5. The thermocouple readings are observed at the inlet and outlet of the test section until a steady state is obtained which is reached after (30-40) minutes.
6. After the steady state is reached, the following readings are recorded: temperature, flow rate, power, and pressure drop. The procedure is repeated for the other concentrations of the nanoparticle. The magnets is fixed on the pipe and repeat all the steps above for each type of magnets.

5. Results and Discussion

Figures (2) show comparison of present experimental work with results Gnielinski's equation and Blasius equation ($f = 0.316Re^{-0.25}$), for distilled water to validate the rig performance. The variation of the Nusselt number with Reynolds number with different magnetic field intensity and ferrofluid concentration along the tube is shown in Figures (3). The average Nusselt number was increased with increasing ferrofluid volume concentration and with increasing magnetic intensity for each concentration, and it was increased with increasing Reynolds number, because, the effective thermal conductivity of nanofluid increases with increasing volume fraction of the nanoparticles, which is explained by Brownian motion of the nanoparticles, molecular level layering of the liquid at liquid/particle interface (wetability).

Enhanced thermal conductivity reduces resistance to thermal diffusion in the laminar sublayer of the boundary layer. Figures (4) the effect of Reynolds number on average Nusselt number with different magnets and (5) represent the effect of Reynolds number on average Nusselt number with different volume concentration. The enhancement in Nusselt number of the magnetic nanofluid with respect to the water reach the maximum value by (5.4 %, 26.4 %, 42.7 %) for ferrofluid volume concentration (0.3, 0.6, 0.9 %) respectively. Also, for magnetic intensity (0.1, 0.2, and 0.3 Tesla) with volume concentration (0.9 %), the enhancements were (43.9, 44.3, and 46 %) respectively. The enhancement with magnetic field is due to the viscous sublayer become very small (at the entrance region), the accumulation of the particle on the surface, and increasing in fraction, all these reason resulted the enhancement in heat transfer. Figure (6) represents the effect of volume concentration on Nusselt number with different flow rate of the ferrofluid the change of properties of fluid by adding nanoparticle cause enhancement in thermal properties and increase Nusselt number with increased volume concentration. The comparison of the present experimental results with the published work, of Sundar [2], is shown in Figure, (7) Nusselt number versus Reynolds number and (8) for friction factor versus Reynolds number. The pressure drop, increases with increased Reynolds number, ferrofluid concentration and the magnetic field intensity. Figures (9) shows the variation of friction factor with Reynolds number. The friction factor increased with increasing the volume concentration because increased in density of fluid resulted increased in pressure drop and the effect of intensity of magnet because drawn the fluid to a surface of pipe and increased fraction. Decreasing fraction with increased Reynold number. Figures (10) show the effect of Reynolds number on friction factor with different magnets**.** And (11) show the effect of Reynolds number on friction factor with different volume concentration. The correlations between Nusselt number and Reynolds number are made by using power method for the working fluid with and without magnetic field with Reynold number range (2950-9820).

$$Nu = CRe^m \qquad \dots (22)$$



(a) **(b)**

Fig. 2. (a) The effect of Reynolds number on Nusselt number for distilled water with Gnielinski's equation, (b) The effect of Reynolds number on friction for distilled water with Blasius equation.

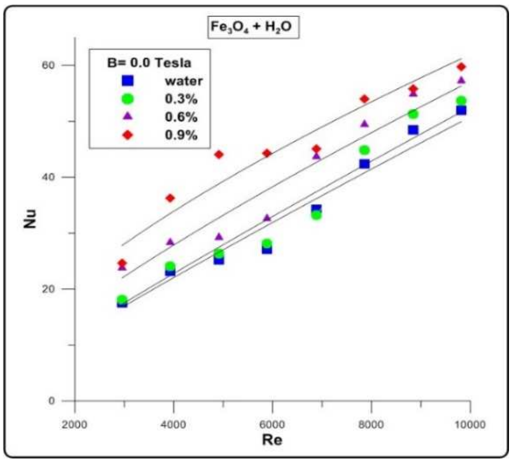
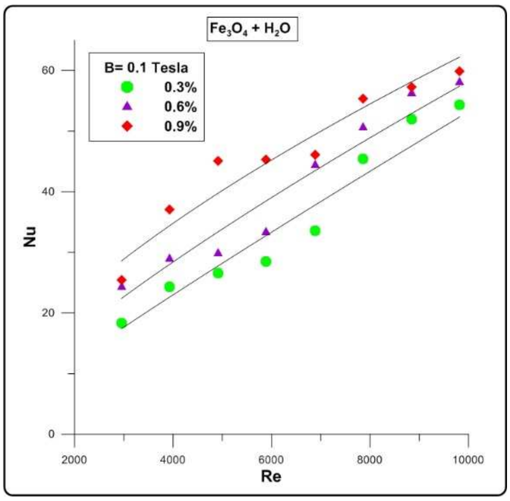
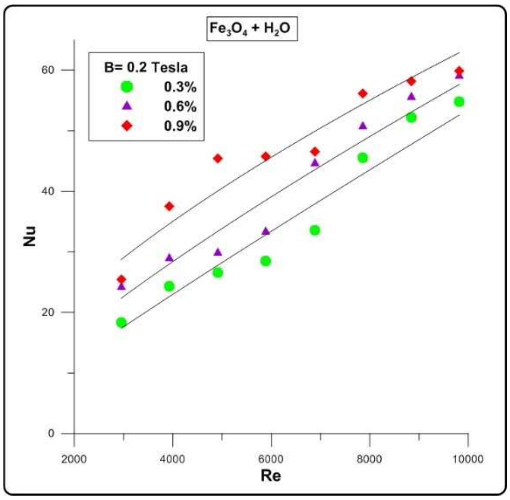


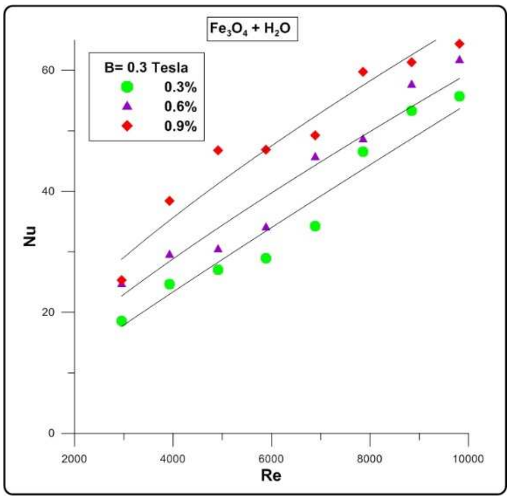
Fig. 3. The effect of Reynolds number on average Nusselt number.



(a)

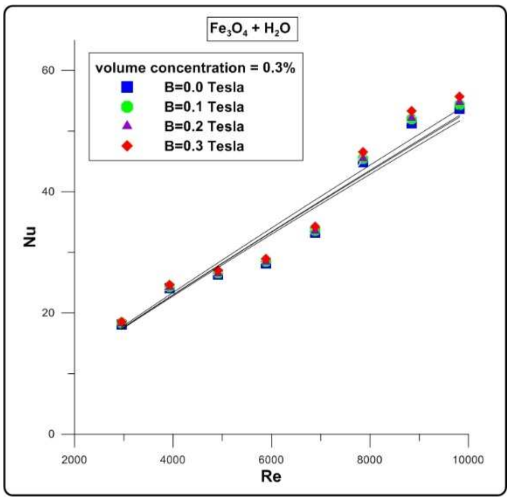


(b)



(c)

Fig. 4. The effect of Reynolds number on average Nusselt number with different magnets.



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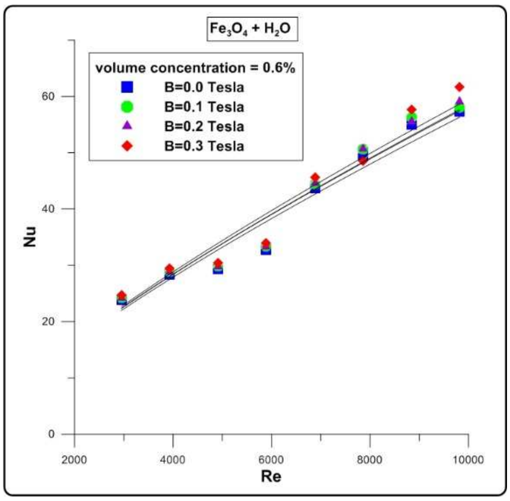

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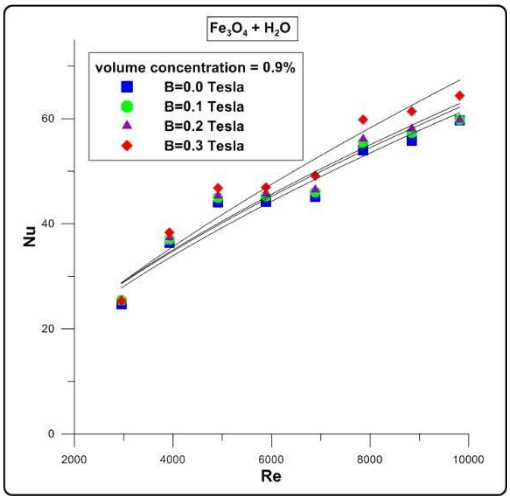


(c)

Fig. 5. The effect of Reynolds number on average Nusselt number with different volume concentration.

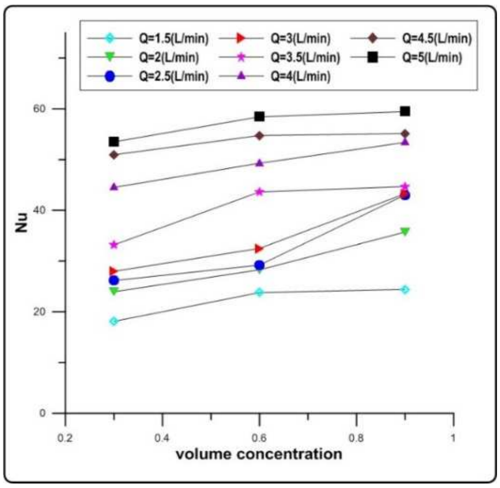


Fig. 6. The effect of volume concentration on Nusselt number.

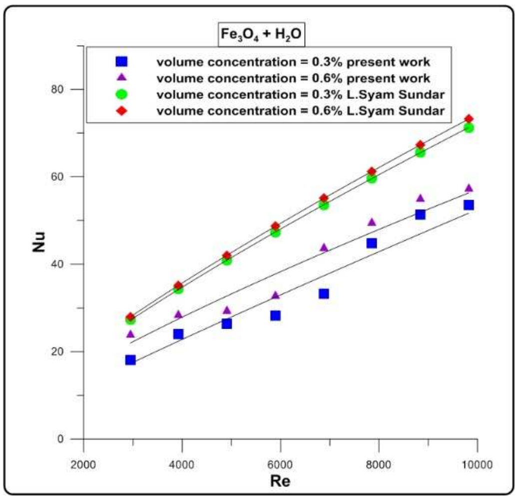


Fig. 7. Comparison of experimental data of the present work with the L.syam Sundar, the effect of Reynold on Nusselt number.

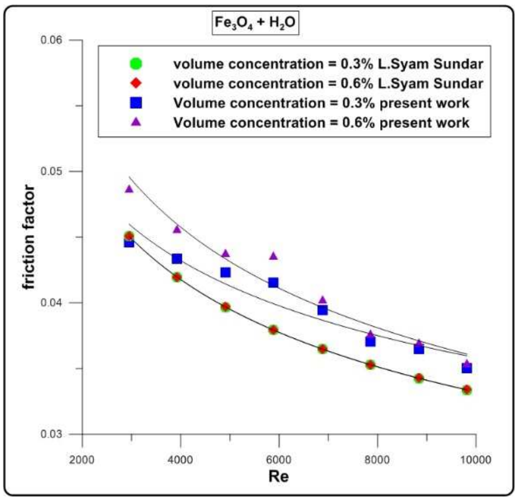


Fig. 8. Comparison of experimental data of the present work with the L.syam Sundar, the effect of Reynold on friction factor.

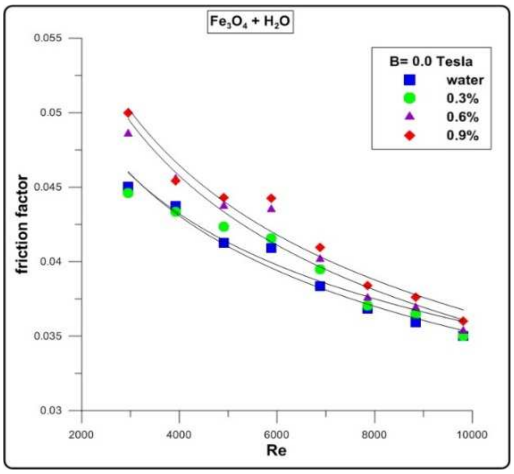
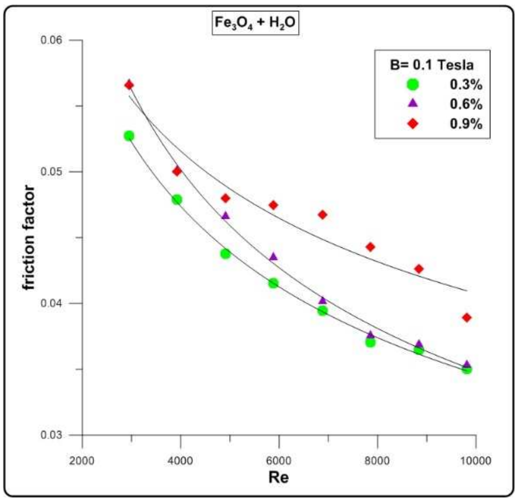
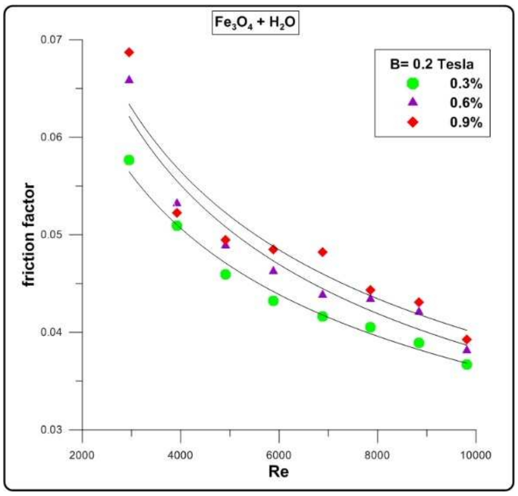


Fig. 9. The effect of Reynolds number on friction factor.



(a)



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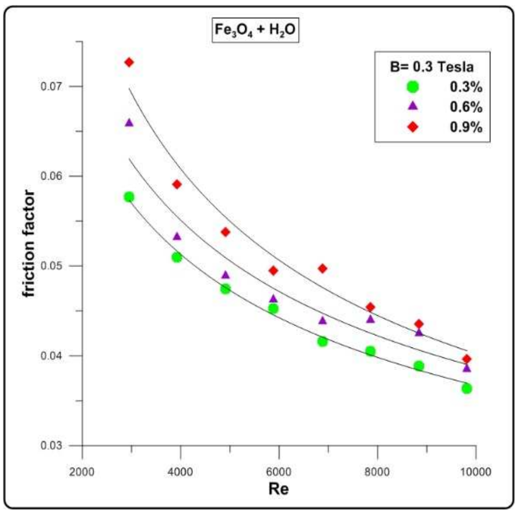
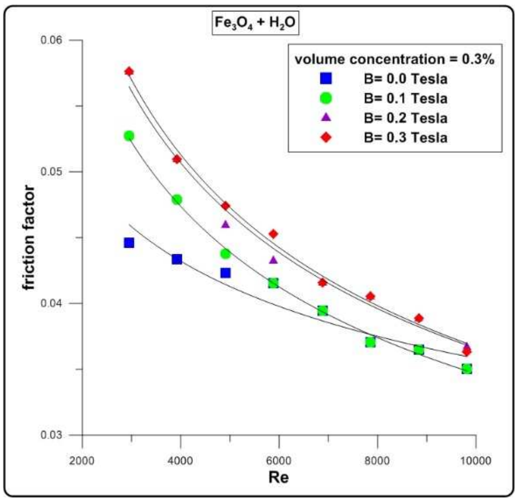


Fig. 10. The effect of Reynolds number on friction factor with different magnets.



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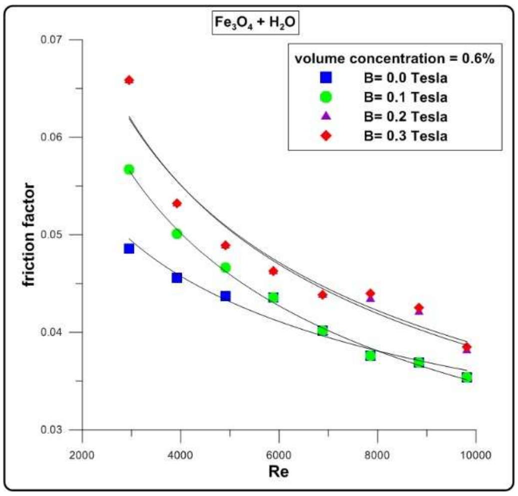

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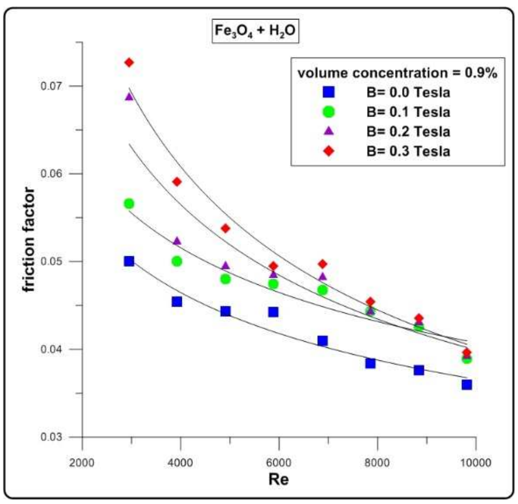

Fig. 11. The effect of Reynolds number on friction factor with different volume concentration.

6. Conclusions

The following points can be concluded from the present work:

1. The magnetic nanofluid Fe_3O_4 (80 nm) – distilled water shows more heat transfer enhancement and higher Nusselt number. The nanoparticles give higher heat transfer characteristics than the base fluid (distilled water). The maximum enhancement is (46%) acheived for magnetic nanofluid with concentration 0.9 % and magnetic field 0.3 Tesla and the minimum enhancement is (3.2 %) established for magnetic nanofluid with concentration 0.3 % without magnetic field.
2. The heat transfer enhanced with increasing nanoparticles concentration.
3. The use of magnetic field increases the heat transfer enhancement, because the magnetic field gives higher Nusselt number compared to water-distilled and magnetic nanofluid. The Heat transfer enhanced with increasing magnetic intensity.
4. Experimental measurements of the Darcy friction factor of magnetic nanofluid give good agreement with the theoretical results of the friction factor from the correlation $f = 0.316Re^{-0.25}$ for water the maximum deviation is (9.75%).
5. The ferrofluid will not cause a penalty drop in pressure but a little increase in pressure drop, for distilled water is (75-548 pa) and (104-635 pa) for nanofluid with constration (0.9%) and magnetic intensity (0.3Tesla). With Reynold number rang (2950-9820) and there is no need for additional pump power.

Nomenclature

A_s	Cross-sectional area (m^2)
B	Magnetic field (Tesla)
C	Specific heat (J/kg.K)
D	Diameter (m)
f	Friction factor
h	Heat transfer coefficient($W/m^2.K$)
I	Current (A)
k	Thermal conductivity (W/m.K)
l	Length of the test section (m)
$\dot{m}$	Mass flow rate (kg/s)
Nu	Nusselt number (-)
Pr	Prandtl number (-)
Q	Heat transfer rate (W)
q	Heat flux (W/m^2)
r	Radius of pipe (m)
Re	Reynolds number (-)
T	Temperature (K)
t	time (sec)
u	Velocity (m/s)
V	Voltage (volts)
γ	Specific weight
ΔP	Pressure drop across the tube
ρ	Mass density (kg/m^3)
φ	Volume fraction of nanofluid Subscripts
CCl_4	Carbon tetrachloride
f	fluid
H	heat
(i,o,s)	in , out ,surface
m	mean
n_f	Nanofluid
P	Particle
pf	Particle fluid
v	vessel (aluminum vessel)
w	Water
x	Distance

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تأثير المجال المغناطيسي مع السوائل متناهية الصغر على انتقال الحرارة في انبوب افقي

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الخلاصــة

تم في هذا البحث إجراء دراسة عملية في انتقال الحرارة والجريان للمائع المتناهي الدقة في أنبوب أفقي مسخن بثبوت الفيض الحراري. تمت الدراسة العملية بأستخدام مائع متناهي الدقة مكون من الماء المقطر ورابع اوكسيد الحديد الممغنط (Fe_3O_4 (80nm) – distilled Water) ضمن تراكيز (φ = 0.3, 0.6, 0.9 %) حجمية كذلك استخدم مغانط ثابتة الشدة (0.1, 0.2, 0.3 tesla) في البحث. تم اجراء كافة التجارب في جريان اضطرابي لمدى عدد رينولد (٢٩٠٠-٩٨٢٠) ومدى فيض حراري (١١٢٦٢-١٩٥٦٢ W/m^2). تم ملاحظة للمائع المتناهي الصغر انه كلما يزداد التركيز يزداد عدد نسلت وان اعظم تحسين للمائع الممغنط المتناهي الصغر كان (% 42.7 ,% 26.4 ,% 5.4) للنسب الحجمية (% 0.3, 0.6, 0.9) على التوالي واعظم تحسين بوجود مجال مغناطيسي ثابت مقداره (0.1,0.2,0.3 tesla) هو (% 43.9,44.3,46) على التوالي مع نسبة حجمية (% 0.9) , ونسبة التحسين تقل مع زيادة عدد رينولد مع حالة استخدام المجال المغناطيسي. معامل الاحتكاك يزداد مع زيادة النسبة الحجمية ويزداد مع زيادة شدة المجال المغناطيسي ويقل مع زيادة عدد رينولد.