Improvement of cooling performance of hybrid nanofluids in a heated pipe applying annular magnets

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Abstract
In this paper, convective heat transfer of Fe₃O₄–carbon nanotubes (CNTs) hybrid nanofluid was studied in a horizontal small circular tube under influence of annular magnets. The pipe has an inner diameter of 3 mm and a length of 1.2 m. Heat transfer characteristics of the Fe₃O₄–water nanofluid were examined for many parameters, such as nanoparticle volume fraction in the range of 0.4–1.2% and Reynolds number in the range of 476–996. In order to increase the thermal conductivity of the Fe₃O₄–water nanofluid, carbon nanotubes with 0.12–0.48% volume fraction were added into the nanofluid. It was observed that for the Fe₃O₄–CNTs–water nanofluid with 1.44% volume fraction and under a magnetic field, the maximal local Nusselt number at the Reynolds number 996 increased by 61.54% compared with without a magnetic field. Results also show that compared with the deionized water, the maximal enhancements of the average Nusselt number are 67.9 and 20.89% for the Fe₃O₄–CNTs–water nanofluid with and without magnetic field, respectively.

Keywords Magnetic nanofluid · Ferrofluid · Convective heat transfer · Carbon nanotube · Magnetic field

Abbreviations

B Magnetic flux density, T
Bₜ Remnant magnetic flux density, T
cₚ Specific heat at constant pressure, J kg⁻¹ K⁻¹
D Diameter, m
F Force, N
h Local heat transfer coefficient, W m⁻² K⁻¹
H Magnetic field, A m⁻¹
I Current, A
k Thermal conductivity, W m⁻¹ K⁻¹
kₒ Thermal conductivity of stainless steel, W m⁻¹ K⁻¹
L Length, m
Nu Nusselt number
Pr Prandtl number
Q Flow rate, m³ s⁻¹
q Heat flux based on thermal power, W m⁻²
qₜ Thermal power, W
Re Reynolds number
T Temperature, K
U Velocity, m s⁻¹
V Voltage, V
x Axial distance from the entrance, m

Greek symbols

α Thermal efficiency
η Heat transfer enhancement percentage in comparison with distilled water, %
µ Dynamic viscosity, Pa s
µₒ Permeability of free space, N A⁻²
µᵣ Relative permeability
ρ Density, kg m⁻³
φ Nanoparticle volume fraction
χᵢ Magnetic susceptibility

Subscripts

avg Average
b Bulk
and pressure loss of CuO–water nanofluid was higher than
Reynolds numbers. They found that heat transfer efficiency
sink by changing nanoparticle volume fractions, sizes and
CuO–water nanofluids in a rectangular microchannel heat
of a mini-channel heat sinks filled with TiO2–water nano-
materials. Wang et al. [12] showed a large enhancement in convective
heat transfer by using Fe3O4–water nanofluid in a stainless
steel pipe under a permanent magnetic field. Fe3O4–water
nanofluid with a magnetic cannula showed heat transfer
enhancements of 26.5% and 54.5% at Re = 391 and 805,
respectively. Hosseinipour et al. [9] investigated the effect of surfactants on heat trans-
flector and pressure drop of multi-walled carbon nanotubes
(MWCNT)–water nanofluids in a circular tube. They found
that the MWCNT–water nanofluid with arginine showed
better heat transfer performance than that with gum Arabic
at the same concentrations.

Magnetic nanofluids have been widely used in different
fields, such as thermal engineering [10] (heat exchanger,
solar collector, air conditioning system, etc.), bioengineer-
ing and optical [11] and sealing technology. The magnetic
nanofluid has remarkable potential for heat transfer appli-
cations because heat transfer process can be controlled by
varying the strength and orientation of the magnetic field.
Wang et al. [12] showed a large enhancement in convective
heat transfer by using Fe3O4–water nanofluid in a stainless
steel pipe under a permanent magnetic field. Fe3O4–water
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Introduction

With increasing serious problems of global environmental
pollution and energy shortages, energy conservation and
environmental protection have become important themes
of common concern in the world. Heat transfer efficiency
in heat exchange systems is needed to be enhanced to
effectively save energy. However, traditional fluids have
low thermal conductivity, which is difficult to meet heat
transfer requirements under some special conditions. One
focus of heat transfer studies is how to find a novel heat
transfer fluid to replace the traditional fluid for the improve-
ment of the heat transfer efficiency. In the past 20 years,
numerous researchers have studied heat transfer character-
istics of various nanofluids. Usually, the nanofluid shows
significant improvement in heat transfer performance of
conventional fluids water, glycol, oil, and etc. Ali et al. [1]
performed heat transfer performance of ZnO–water nano-
fluid in a car radiator with ranges of Reynolds numbers,
volume fractions, and inlet temperatures of 7500–27,600,
0.01–0.3% and 45–55 °C, respectively. Results indicated
that when the volume fraction of the nanofluid was 0.2%,
the heat transfer performance of the car radiator was 46%
higher than base fluid. Sajid et al. [2] studied heat transfer
of a mini-channel heat sinks filled with TiO2–water nano-
fluid. Results indicated that 0.012 vol.% TiO2–water nano-
fluid showed a maximum enhancement of 40.57% in Nusselt
number compared to water at Re = 894. Ebrahimi et al. [3]
investigated heat transfer performance of Al2O3–water and
CuO–water nanofluids in a rectangular microchannel heat
sink by changing nanoparticle volume fractions, sizes and
Reynolds numbers. They found that heat transfer efficiency
and pressure loss of CuO–water nanofluid was higher than
those of Al2O3–water nanofluid at the same conditions.
Shanbedi et al. [4] examined the thermal conductivity of
multi-walled carbon nanotubes–water nanofluid. Their
results demonstrated that the thermal conductivity of the
metal nanoparticles-decorated carbon nanotubes nanofluid
was higher than that of gum Arabic decorated carbon nano-
tubes nanofluid. Zheng et al. [5] investigated effects of mag-
netic fields on flow characteristics and thermal performance
of a plate heat exchanger filled with a magnetic nanofluid.
They found that appropriate magnet arrangement resulted in
good thermal performance and low flow resistance simulta-
nceously. Kumar and Chandrasekar [6] analyzed heat transfer
performance of multiwall carbon nanotube–water nanofluids
in a double helically coiled tube heat exchanger, and they
found that 35% heat transfer was enhancement is obtained
for the 0.6 vol.% MWCNT–water nanofluid at a Dean num-
ber of 1200. Dabiri et al. [7] experimentally studied heat
transfer characteristics of SiC–water and MgO–water nano-
fluids inside a circular tube. Results showed that an increase
in heat transfer enhancement was observed by increasing
volume concentration and Reynolds number. Sarafruz et al.
[8] experimentally investigated convective heat transfer of
carbon nanotube–water nanofluid inside a double pipe
heat exchanger, and their results revealed that by adding 0.3
mass% carbon nanotubes into the base fluid, the thermal
conductivity was enhanced by at most 56%. Hosseinipour
et al. [9] investigated the effect of surfactants on heat trans-
flector and pressure drop of multi-walled carbon nanotubes
(MWCNT)–water nanofluids in a circular tube. They found
that the MWCNT–water nanofluid with arginine showed
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at the same concentrations.

Hybrid nanofluids are prepared by dispersing various
types of nanoparticles into a base fluid. It is found that
hybrid nanofluids show enhancements of heat transfer performance and improvements of thermophysical properties compared with conventional fluids. Many scholars numerically and experimentally carried out heat transfer analysis of hybrid ferrofluids under an external magnetic field. Shahsavar et al. [17] investigated heat transfer in a heated pipe filled with a Fe₃O₄–carbon nanotubes (CNTs) hybrid nanofluid. They concluded that 0.5 vol% Fe₃O₄ and 1.35 vol% CNTs hybrid nanofluid showed a maximum enhancement of 62.7% in the local Nusselt number, compared with water at Re = 2190. Harandi et al. [18] analyzed the thermal conductivity of Fe₃O₄–carbon nanotubes–ethylene glycol (EG) hybrid nanofluid, and found that the thermal conductivity of the nanofluid was enhanced by 30% at 50 °C and 2.3% volume fraction. Askari et al. [19] investigated thermal characteristics of a Fe₃O₄–graphene nanofluid. It was observed that compared to the base fluid, the thermal conductivity of the nanofluid was enhanced up to 32% at 1% mass fraction and 50 °C. Askari et al. [20] measured the effect of hybrid Fe₃O₄–graphene nanoparticles on the thermal conductivity of water. Results revealed that a maximum increase of 31% of the thermal conductivity was achieved for 1 mass% nanoparticle concentration at 50 °C. Nadoushan et al. [21] examined the viscosity of Fe₃O₄–MWCNTs–ethylene glycol hybrid nanofluid in a temperature range of 25–50 °C and various solid volume fractions (0.1, 0.25, 0.8, 1.25 and 1.8%). Results showed that the examined hybrid nanofluid exhibited a Newtonian behavior, and higher volume fraction of the nanofluid resulted in higher viscosity. Farbod and Ahangarpour [22] investigated thermal conductivity of a MWCNTs–Ag–water nanofluid in a temperature range of 20–50 °C. It was found that compared with the MWCNTs–water nanofluid, the MWCNTs–Ag–water nanofluid with 4% Ag had a maximum enhancement of 20.4% in thermal conductivity.

The available studies on the heat transfer performance of the magnetic nanofluids have mainly focused on a single species of particles under a magnetic field. This means that the existing experimental data is insufficient for evaluation of heat transfer performance of hybrid magnetic nanofluids in a heat transfer system. This paper aims to investigate laminar convective heat transfer of Fe₃O₄–water and Fe₃O₄–CNTs–water nanofluids in a straight stainless steel pipe in presence of a magnetic field. Effects of the layout of magnets, Reynolds number and nanoparticle volume fraction on heat transfer characteristics of various nanofluids are analyzed by the experimental tests.

**Experimental**

**Particle characterization, ferrofluid preparation and stability**

In the present research, Fe₃O₄ nanoparticles were prepared by chemical coprecipitation method, and multi-wall carbon nanotubes (MWCNTs) were provided by Chengdu Organic Chemicals Co. Ltd., Chinese Academy of Sciences. These CNTs have a true density of 2.1 g cm⁻³ [21], outer diameter of 8–15 nm, with a purity of more than 99.9%. Using transmission electron microscopy (TEM) and scanning electron microscopy (SEM), micrographs of the nanoparticles Fe₃O₄ and CNTs are shown in Fig. 1. It is observed that the nanoparticle Fe₃O₄ has an average diameter of 15 ± 5 nm.

The photographs of Fe₃O₄–water and Fe₃O₄–CNTs–water nanofluids are provided in Fig. 2. Carbon nanotubes (CNTs) were chemically functionalized by potassium persulfate solution with pH = 13 at 85 °C. CNTs and surfactants were weighed by an electronic balance. The CNTs with surfactants were mixed into distilled water. The mixed solution was stirred by a mechanical stirrer at 1500 r min⁻¹ and dispersed by an ultrasonic cleaner for 60 min. The power and frequency of the ultrasonic cleaner were 380 W and 40 kHz, respectively. Fe₃O₄ magnetic nanoparticles and trisodium...
citrate dehydrate (TSC) with a ratio of 8:1 were used to synthesize a magnetic nanofluid. The CNTs and Arabic gum with a mass ratio of 5:1 were dispersed into the Fe₃O₄–water nanofluid. Zeta potentials of samples were measured using a ZS-90 zeta potential analyzer (Malvern Co., Ltd., UK). The stability of the nanofluid can be evaluated by measuring the zeta potential of the nanofluid. When the zeta potential value of the nanofluid is higher than 30 mV, it is considered that the nanofluid has a better stability. The zeta potentials of the 1.2% Fe₃O₄–water and 1.32% Fe₃O₄–CNTs–water nanofluids are −31.6 ± 7.4 mV and −30.8 ± 6.94 mV, respectively, which indicate that these nanofluids have good dispersion stability. Sedimentation of nanoparticles is investigated in a silicone pipe with a length of 20 cm, an outer diameter of 5 mm, and an inner diameter of 3 mm. The 1.2% Fe₃O₄–water and 1.44% Fe₃O₄–CNTs–water nanofluids are kept at experimental operation for two hours. In order to obtain high accuracy of the experimental data, the tests are repeated 5 times. For the 1.2% Fe₃O₄–water and 1.44% Fe₃O₄–CNTs–water nanofluids, the mass of the silicone tube before and after the tests increased by 0.12 and 0.13% (average value) respectively. The results reveal that a little sedimentation appears for the Fe₃O₄–CNTs–water nanofluid during the tests. Figure 3 presents the zeta potential distributions of the two nanofluids. Table 1 shows density (ρ), thermal conductivity (k), dynamic viscosity (μ) and specific heat (C_p) of the base fluid and nanoparticles.

Viscosities of the nanofluids are obtained using a Brookfield DV2T viscometer. According to Fig. 4, it is revealed that the viscosity is directly proportional to the volume concentration of nanoparticles. Compared with distilled water, the average viscosity of 1.68 vol% Fe₃O₄–CNTs–water nanofluid is increased by 109.6%. Figure 5 shows the viscosity of the two nanofluids as a function of shear rate at 25 °C. The viscosities of the Fe₃O₄–water nanofluid and the deionized fluid are almost constant with increasing shear rate, which indicates a Newtonian fluid behavior. For the Fe₃O₄–CNTs–water nanofluid, an increase of the shear rate results in a reduction of the viscosity, showing a non-Newtonian behavior of shear thinning. Generally, it is considered that the shear thinning behavior is caused due to a reduction of suspended particle clusters under shear force.
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Magnet arrangement

Geometry information of magnets and cannulas are presented in Fig. 7. Forced convective heat transfer in the pipe is investigated by changing the number of the magnets as in the previous research [12]. The cannulas are used to generate various magnetic fields perpendicular to the
test section. Figure 8 shows three arrangements of cannulas under non-uniform permanent magnetic fields, i.e., case I, case II and case III. Data of the magnets is summarized in Table 2.

### Analysis of experimental data

Nusselt number (\( Nu \)) is defined by:

\[
Nu = \frac{hD_i}{k}
\]

where \( k \) is thermal conductivity of the fluid at 25 °C, \( D_i \) is inner diameter of a stainless steel pipe. \( h \) in Eq. (1) is the local heat transfer coefficient and calculated as:

\[
h = \frac{q''}{T_{w,i}(x) - T_b(x)}
\]

where the variable \( x \) is the axial distance from the inlet of the stainless steel pipe, and \( q'' \) is the heat flux. The fluid temperature \( T_b(x) \) is obtained by the following equation:

\[
T_b(x) = \frac{q'' \pi D_o}{\rho \rho C_p} x + T_{in}
\]

where \( Q \) and \( \rho \) are volume flow rate and density of the working fluid, respectively. Due to the small inner diameter (3 mm) and a uniform heating of the pipe, the wall heat conduction along the axial direction is ignored and the heat conduction in the circumferential direction is uniform. Therefore, the heat conduction in the tube wall is approximated as a one-dimensional heat transfer problem with an internal heat source along the radial direction. The inner wall temperature \( T_{w,i}(x) \) is given by:

\[
T_{w,i}(x) = \frac{aVI}{2\pi K_w L} \left[ \frac{D_o^2}{D_o^2 - D_i^2} \log \left( \frac{D_o}{D_i} - 0.5 \right) \right]
\]

where \( K_w \) and \( D_o \) are thermal conductivity and outer diameter of the stainless steel pipe, respectively. The heat flux \( q'' \) is calculated as:

\[
q'' = \frac{aVI}{\pi D_o L}
\]

where \( L \) is the length of the stainless steel pipe. \( I \) and \( V \) are the given current and voltage, respectively. Based on a series of thermal equilibrium tests using deionized water, the thermal efficiency is determined to be 0.93 ± 0.015. The thermal efficiency \( \alpha \) of the test section is calculated by:

### Table 2: Data of permanent magnets

| Parameters                          | Description                  |
|-------------------------------------|------------------------------|
| Magnetic type                       | NdFeB (Neodymium) N42        |
| Maximum operating temperature       | 80 °C                        |
| Surface field                       | 0.3332 T                     |
| Residual flux density \((B_{r\text{max}})\) | 1.32 T                       |
| Maximum energy product \((B_{H\text{max}})\) | 42 MGOe                      |
| Relative permeability \((\mu_r)\)   | 1.05                         |
| Magnetic permeability of free space \((\mu_0)\) | \( 4\pi \times 10^{-7} \text{ N A}^{-2} \) |
\[ a = \frac{Q_m C_p(T_{in} - T_{out})}{V I} \]  

where \( Q_m \) is the mass flow rate. The density \( \rho_{ff} \), specific heat \( C_p_{ff} \) and thermal conductivity \( k_{ff} \) of the hybrid nanofluid are calculated as shown in Ref. [23]:

\[ \rho_{ff} = \varphi_1 \rho_1 + \varphi_2 \rho_2 + (1 - \varphi) \rho_{bf} \]  

(7)

\[ (\rho c_p)_{ff} = \varphi_1 (\rho c_p)_1 + \varphi_2 (\rho c_p)_2 + (1 - \varphi) (\rho c_p)_{bf} \]  

(8)

\[ k_{ff} = \frac{\varphi_1 k_1 + \varphi_2 k_2 + 2 \varphi k_m + 2 \varphi (\varphi_1 k_1 + \varphi_2 k_2) - 2 \varphi^2 k_{bf}}{\varphi_1 k_1 + \varphi_2 k_2 + 2 \varphi k_{bf} - \varphi (\varphi_1 k_1 + \varphi_2 k_2) + \varphi^2 k_{bf}} \]  

(9)

The viscosity of the hybrid nanofluid \( (\mu_{ff}) \) is obtained as follows [24]:

\[ \mu_{ff} = \mu_{bf}(1 + 2.5\varphi) \]  

(10)

The total volume concentration \( (\varphi) \) of nanoparticles \( \text{Fe}_3\text{O}_4 \) and CNTs is obtained by:

\[ \varphi = \varphi_1 + \varphi_2 \]  

(11)

where subscripts 1, 2, p and bf represent physical properties of the \( \text{Fe}_3\text{O}_4 \)-water nanofluid, CNTs-water nanofluid, nanoparticles and the base fluid, respectively.

To evaluate the enhancement of heat transfer by using the hybrid nanofluid, average \( \text{Nu} \) (based on measurements of 9 thermocouples on the test section) and the increased value of the average \( \text{Nu} \) are introduced as

\[ \text{Nu}_{avg} = \frac{\sum_{i=1}^{9} \text{Nu}_i}{9} \]  

(12)

Uncertainty analysis

Uncertainties of measurements are summarized in Table 3. The viscosity measurement (Brookfield DV2T viscometer) have an accuracy of 1%. The accuracy of the thermocouples after calibration is 0.1 °C. The voltage and current values used in the tests are 2.85 ± 0.1 V and 18.25 ± 0.01 A, respectively. According to the uncertainty analysis of the experimental results described in Ref. [25], the maximum uncertainty of the parameter \( R \) is calculated as

\[ \text{Max. } U_R = \pm \sqrt{\left( \frac{s_1}{R} \frac{\partial R}{\partial U_1} \right)^2 + \left( \frac{s_2}{R} \frac{\partial R}{\partial U_2} \right)^2 + \cdots + \left( \frac{s_n}{R} \frac{\partial R}{\partial U_n} \right)^2} \]  

(14)

where \( U_R \) is the maximum error of the parameter \( R \). \( s \) is measurable parameter, and \( U_i \) is measured error. The maximum uncertainties of \( V, I, q, \text{Re}, h \) and \( \text{Nu} \) are determined by:

\[ U_V = \frac{0.1}{2.85} = \pm 0.03509 \]  

(15)

\[ U_I = \frac{0.01}{18.25} = \pm 5.749 \times 10^{-4} \]  

(16)

\[ \text{Max. } U_q = \pm \sqrt{(U_i)^2 + (U_V)^2} = \pm 3.51% \]  

(17)

\[ \text{Max. } U_{\text{Re}} = \pm \sqrt{(U_p)^2 + (U_q)^2 + (U_D)^2 + (U_L)^2 + (U_T)^2} = \pm 3.62% \]  

(18)

\[ \text{Max. } U_h = \pm \sqrt{(U_c)^2 + (U_p)^2 + (U_Q)^2 + (U_{T_{out}-T_{in}})^2 + (U_{T_{out}-T_{in}})^2} = \pm 8.99% \]  

(19)

\[ \eta = \frac{\text{Nu}_{avg,ff} - \text{Nu}_{avg,bf}}{\text{Nu}_{avg,bf}} \]  

(13)

Results and discussion

Simulation analysis of Magnetic field

The software COMSOL Multiphysics 5.2 has been used to simulate the magnetic flux density and magnetic force distribution for three cases as shown in Fig. 8. The magnetic flux
density and the magnetic force distribution are calculated as
in https://www.comsol.com and Ref. [26]:

\[
\vec{B} = \mu_0 \mu_i H + B_i \tag{21}
\]

\[
\vec{F}_M = V_p \chi_i \vec{B} \nabla \cdot \vec{B} \tag{22}
\]

where \( H \) is the magnetic field, and \( B_i \) is the residual magnetic flux density. \( B \) is the magnetic flux density. \( \mu_0 \) is the magnetic permeability of the free space, and \( \mu_i \) is the relative permeability. \( V_p \) is the nanoparticle volume, and \( \chi_i \) is the magnetic susceptibility of the magnetite nanoparticles. The magnetic flux density of unsaturated ferromagnetic material lags behind the magnetic field intensity, which is called a phenomenon of hysteresis. When the magnetic field intensity drops to zero, the corresponding magnetic flux density \( B \) is called the remnant magnetic flux density (\( B_r \)).

The reliability of the present simulated results is validated by comparisons with results in Ref. [27]. In Fig. 9, it is found that the simulation results show good agreement with the results of reference [27].

The geometric structure in the case I is shown in Fig. 10a. The tube diameter and magnet size in the numerical simulations are consistent with the experimental structure as shown in Fig. 7. A cross section of the pipe (80 mm) near the magnets is used for simulations. The grid independence study is conducted using 0.86, 1.68 and 3.15 million grid cells as shown in Fig. 10b. By comparing the magnetic flux density along the center line of the pipe in the case with 3.15 million cells, it is found that the case with the 1.68 million cells shows almost no difference. So, the 1.68 million cells are used in this research.

In order to investigate the effect of magnetic field strength, two magnets packaged in a cannula were placed outside the pipe. Figure 11 shows distributions of magnetic flux density (\( B \)) on cross planes (Section A–A) through the pipe centerline for case I (one cannula), case II (two adjacent cannulas) and case III (three adjacent cannulas). \( B \) between magnets for case I shows a symmetric distribution. The magnetic flux density (\( B \)) and magnetic force (\( F_m \)) along the
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The magnetic force along the centerline of the pipe has a similar periodic distribution. The maximum values of $B$ exist near the edges of the magnets as shown in Figs. 11 and 12. It is also proved that large $F_m$ exist at the edges of the magnets (dashed line in Fig. 12) based on a direct relation between magnetic flux density gradient and $F_m$ from Eq. (22). It can be found that the peak values of $B$ for two adjacent cannulas (case II) and three adjacent cannulas (case III) are higher than that for the one cannula (case I).

The $B$ distributions of the magnetic flux density for one cannula, two cannulas and three cannulas show two extremum values, four extremum values and six extremum values, respectively. The maximum values of $B$ and $F_m$ (case II) along the centerline of the pipe are 166.9 mT and 3.68 x 10^{-17} N, respectively. For case III, the maximum values of $B$ and $F_m$ along the centerline of the pipe are 167.8 mT and 3.63 x 10^{-17} N, respectively. It is found that the maximum magnetic force hardly changed in these three cases.

Validation of test data

In order to verify the reliability of the experimental results, an experimental validation is conducted at various Re numbers (476, 663 and 996) by using DI-water as the working fluid. The reliability of the experimental data is analyzed based on the results in Fig. 13. It is found that a good agreement between the present experimental data and theoretical values (The error is less than 10%) calculated by Eq. (23) in Ref. [28]:

$$\begin{equation}
\text{Nu} = \begin{cases}
1.302 \left( \frac{\text{d}B}{\text{d}x} \right)^{-1/3} - 0.5 & 0.0005 \leq \frac{\text{d}B}{\text{d}x} \leq 0.0015 \\
4.364 + 0.263 \left( \frac{\text{d}B}{\text{d}x} \right)^{-0.566} e^{-0.41 \left( \frac{\text{d}B}{\text{d}x} \right)} & \text{d}B/\text{d}x > 0.0015
\end{cases}
\end{equation}
$$

Equation (23) is suitable for laminar convective heat transfer under constant heat flux boundary conditions. This equation is widely used to verify reliability of an experimental system [17, 27].

Magnetic nanofluid without magnetic field

Without a magnetic field, Fig. 14 presents the average Nu of Fe$_3$O$_4$–water nanofluids and Fe$_3$O$_4$–CNTs–water hybrid nanofluids at various Re numbers. It is observed that for these nanofluids, the average Nusselt number is higher than that for the base fluid. Moreover, results indicate that the average Nu of the magnetic nanofluid increases with increases both in Re and nanoparticle volume fraction. The average Nu of the Fe$_3$O$_4$–water nanofluids with volume fractions of 0.4, 0.8 and 1.2% are 1.96, 4.23 and 5.69% higher than that of the base fluid at Re = 476, respectively. When the Reynolds number is increased to 996, the average Nusselt numbers for the 0.4, 0.8 and 1.2% nanofluids are 3.65, 9.54 and 13.34% higher than that of the base fluid, respectively. For the Fe$_3$O$_4$–CNTs–water hybrid nanofluid with 1.32, 1.44 and 1.68% volume fractions, the average Nusselt number increases by 7.66–14.73%, 10.3–17.57% and 12.56–20.89% compared to the base fluid under the Reynolds number of 476–996, respectively. These data indicate that the mixture with a small amount of carbon nanotubes can improve the heat transfer performance of the Fe$_3$O$_4$–water nanofluid.

Fe$_3$O$_4$–water nanofluid with magnetic field

For the case I, case II and case III at Reynolds numbers of 476, 663 and 996, Figs. 15–17 show local Nusselt numbers of Fe$_3$O$_4$–water nanofluids with three volume fractions (0.4, 0.8 and 1.2%) along the dimensionless x axial coordinate ($X/D_i$). For the 0.4 vol% Fe$_3$O$_4$–water nanofluid, the local Nusselt number (Nu) reaches its maximum value nearly at
the thermocouple number T7 for case I and case II. For case III, the maximum value of Nu moves from thermocouple number T7 to T8, as the Re increases. For the case III at the same position, the maximum values of local Nusselt numbers for three cases are 31.16, 34.93 and 47.04% higher than the results without magnetic field at the Reynolds numbers of 476, 663 and 996, respectively. It is found that the presence of the magnetic field results in an enhancement of the convective heat transfer coefficient for all cases at three Reynolds numbers, and three cannulas provides a nearly 50% enhancement of heat transfer. From the temperature values at the position T9, it is concluded that the
heat transfer enhancement is increasing with the increase of the number of magnets, Reynolds number and nanoparticle concentration.

For the 0.8 vol% Fe$_3$O$_4$–water nanofluid as shown in Fig. 16, the Nusselt number reaches its maximum value at thermocouple numbers T5–T6. It is found that with the magnetic field, the maximum values of local Nu for case I, case II and case III are 33.16, 37.36 and 42.85% higher than those without a magnetic field at the same position, respectively. Based on a similar analysis for the 1.2 vol% Fe$_3$O$_4$–water nanofluid as shown in Fig. 17, the maximal value of local Nu increases by 39.81, 53.73, and 61.13% for case I, case II and case III, respectively. This is because nanoparticle aggregation has a great effect on enhancement of convective heat transfer. The quantity of aggregated particles on the inner wall of the pipe is rising with the increase of the volume fraction and the intensity of the magnetic field. Larger local thermal conductivity exists near the position of the magnets due to the effect of the magnetic force. In addition, the aggregation of magnetic nanoparticles destroys the wall boundary layer, which enhances the heat transfer near the pipe wall.

**Fe$_3$O$_4$–CNTs–water nanofluid with magnetic field**

For cases I–III at Reynolds number of 476, 663 and 996, Figs. 18–20 show Nusselt number distributions of Fe$_3$O$_4$–CNTs–water hybrid nanofluids with three volume fractions (1.32, 1.44 and 1.68%) along the dimensionless x axial coordinate (X/D$_i$). It is observed that Nusselt number for cases without magnetic field decreases along the x axial direction, whereas Nusselt number significantly increases when a magnetic field is applied to the hybrid

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**Fig. 13** Nu comparison between test results and calculated values from Eq. (23)

**Fig. 14** Average Nusselt numbers for magnetic nanofluids with various volume concentration and Reynolds numbers
nanofluids. For all the Reynolds numbers and with all the volume fractions, the Nusselt number reaches its maximum value at thermocouple positions T6, T6 and T7 for case I, case II and case III, respectively. Compared with the 1.32 vol% Fe$_3$O$_4$–CNTs–water nanofluid (1.2% Fe$_3$O$_4$ + 0.12% CNTs) at the same position and under no magnetic field, the maximum Nusselt number under three magnetic cannulas increases by 52.57, 56.64 and 59.86% at Reynolds numbers of 476, 663 and 996, respectively.

For the 1.44 vol% Fe$_3$O$_4$–CNTs–water (1.2% Fe$_3$O$_4$ + 0.24% CNTs) nanofluid at the same position, compared with cases I-III without a magnetic field, it is found that Nusselt numbers of the hybrid nanofluids are improved by 45.57, 54.51 and 59.86% at Reynolds numbers of 476, 663 and 996, respectively.

As shown in Ref. [29], for the Fe$_3$O$_4$–CNTs–water hybrid nanofluids, a magnetic force changes the distribution and array of the magnetic nanoparticles and the carbon nanotubes, which results in an increased contact area between magnetic nanoparticles and nanotubes. In addition, nanoparticles CNTs and Fe$_3$O$_4$ under a magnetic field tend to migrate toward the pipe wall. The nanoparticle aggregation will intensify the disturbance of the thermal boundary layer. It is expected that local heat transfer of Fe$_3$O$_4$–CNTs–water hybrid nanofluid is higher than for the Fe$_3$O$_4$–water nanofluid can be improved by 32.79%, 48.74% and 56.88%, compared with cases I-III under no magnetic field, respectively. It is also revealed that Nu of hybrid nanofluid with higher volume fraction increases with increasing Re and quantity of cannulas.
nanofluid due to both higher thermal conductivity and destroyed thermal boundary layer.

Table 4 shows improvements of the maximum Nusselt number for cases with various volume fractions and three Reynolds numbers, after three magnetic fields are applied. It is easily found that for the Fe₃O₄–water nanofluid, the increase in the number of cannulas results in an enhancement of heat transfer.

For the 1.32 vol% Fe₃O₄–CNTs–water (1.2% Fe₃O₄ + 0.12% CNTs) nanofluid, the maximum enhancement of the local Nusselt number is higher than for 1.2 vol% Fe₃O₄–water nanofluid in most cases. This result shows that adding a small amount of multi-walled carbon nanotubes into the Fe₃O₄–water nanofluid can significantly improve the convective heat transfer in the pipe. This finding is also shown in a study about plate heat exchangers [30]. However, the enhancement in heat transfer for the 1.68 vol% Fe₃O₄–CNTs–water nanofluid is smaller than for the 1.2 vol% Fe₃O₄–water nanofluid in all cases. The reason might be that the viscosity of the 1.68 vol% Fe₃O₄–CNTs–water nanofluid under magnetic field is higher than that of 1.2 vol% Fe₃O₄–water nanofluid, which weakens heat transfer in the pipe. It is easily found that compared with cases under no magnetic field, the increase in the maximum Nusselt number is provided by the 1.44 vol% Fe₃O₄–CNTs–water (1.2% Fe₃O₄ + 0.24% CNTs)
hybrid nanofluid under a magnetic field (only exception for two cannula case at Re = 996).

Improvements of the average Nusselt number for various nanofluids are plotted in Fig. 21. Enhancements for the magnetic cases, volume fractions and Reynolds numbers are shown. Results indicate that without a magnetic field the heat transfer increases with volume fractions and Re. When a magnetic field is applied to the pipe (case I, case II and case III), an optimum volume fraction (1.44 vol% Fe$_3$O$_4$–CNTs–water nanofluid) is obtained for each Reynolds number to achieve the maximum heat transfer enhancement. Heat transfer enhancements for the 1.44 vol% Fe$_3$O$_4$–CNTs–water nanofluid with a single magnetic cannula (case I) by 26.6, 31.99 and 34.85% are found at Re = 476, 663 and 996, respectively. Compared with the 1.44 vol% Fe$_3$O$_4$–CNTs–water nanofluid with double magnetic cannulas (case II), the average Nusselt number enhancement at the Reynolds number of 663 is higher than at the Reynolds number of 996. It is found that the maximum improvement of 67.9% of heat transfer is achieved by a dispersion of 1.44 vol% nanoparticles inside the DI-water at high Reynolds number with three magnetic cannulas (case III).
Fig. 18 Variations of Nusselt number vs. dimensionless distance ($X/D_i$) for 1.32 vol% Fe$_3$O$_4$–CNTs–water (1.2% Fe$_3$O$_4$ + 0.12% CNTs) nanofluid in three cases

(a) $Re = 476$

(b) $Re = 663$

(c) $Re = 996$
Fig. 19 Variations of Nusselt number vs. dimensionless distance ($X/D_i$) for 1.44 vol% Fe$_3$O$_4$-CNTs–water (1.2% Fe$_3$O$_4$ + 0.24% CNTs) nanofluid in three cases.

(a) Re = 476  
(b) Re = 663  
(c) Re = 996

Fig. 20 Variations of Nusselt number vs. dimensionless distance ($X/D_i$) for 1.68 vol% Fe$_3$O$_4$-CNTs–water (1.2% Fe$_3$O$_4$ + 0.48% CNTs) nanofluid in three cases.

(a) Re = 476  
(b) Re = 663  
(c) Re = 996
Conclusions

In this study, various volume fractions of nanoparticles $\text{Fe}_3\text{O}_4$ and carbon nanotubes (CNTs) were used to improve the thermophysical properties of the base fluid. Heat transfer characteristics of a $\text{Fe}_3\text{O}_4$–CNTs–water hybrid nanofluid in a heated straight pipe were experimentally investigated and compared with $\text{Fe}_3\text{O}_4$–water nanofluid under magnetic field arrangement and for various Reynolds numbers.

For the 1.2 vol% $\text{Fe}_3\text{O}_4$–water nanofluid, the maximal values of the local Nusselt number increased by 39.81, 53.73, and 61.13% for cases with one cannula, two cannulas and three cannulas, respectively. Compared with $\text{Fe}_3\text{O}_4$–water nanofluid without magnetic field, the heat transfer performance can be significantly improved by increasing the number of magnetic cannuas. When 0.12% carbon nanotubes are added into 1.2%
Fe3O4–water nanofluid, the maximum enhancement of the local Nusselt number is increased. Compared with cases under no magnetic field, a nanofluid with 1.2% Fe3O4 nanoparticles and 0.24% carbon nanotubes shows the maximum Nusselt number under a magnetic field in most cases.

The presence of the magnetic field improves the convective heat transfer in the pipe due to the increase in thermal conductivity, the enhancement of turbulence, and the disturbance of the thermal boundary layer. The hybrid magnetic nanofluid might be a potential cooling medium for further enhancement of the heat transfer performance.

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