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
B_r	Remnant magnetic flux density, T
c_p	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
k_w	Thermal conductivity of stainless steel, W m ⁻¹ K ⁻¹
L	Length, m
Nu	Nusselt number
Pr	Prandtl number
Q	Flow rate, m ³ s ⁻¹
q''	Heat flux based on thermal power, W m ⁻²
q	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
μ_0	Permeability of free space, N A ⁻²
μ_r	Relative permeability
ρ	Density, kg m ⁻³
φ	Nanoparticle volume fraction
χ_i	Magnetic susceptibility

Subscripts

avg	Average
b	Bulk

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bf	Base fluid
ff	Ferrofluid
in	Inlet
i	Inside
M	Magnetic
out	Outlet
o	Outside
p	Particle

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 improvement of the heat transfer efficiency. In the past 20 years, numerous researchers have studied heat transfer characteristics 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 nanofluid 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 nanofluid. Results indicated that 0.012 vol.% TiO₂–water nanofluid 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 nanotubes nanofluid. Zheng et al. [5] investigated effects of magnetic 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 simultaneously. 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 enhancement is obtained for the 0.6 vol.% MWCNT–water nanofluid at a Dean number of 1200. Dabiri et al. [7] experimentally studied heat transfer characteristics of SiC–water and MgO–water nanofluids inside a circular tube. Results showed that an increase in heat transfer enhancement was observed by increasing volume concentration and Reynolds number. Sarafraz 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 transfer 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.), bioengineering and optical [11] and sealing technology. The magnetic nanofluid has remarkable potential for heat transfer applications 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 nanofluid with a magnetic cannula showed heat transfer enhancements of 26.5% and 54.5% at Re = 391 and 805, respectively. Hosseinzadeh et al. [13] analyzed heat transfer and friction factor of Fe₃O₄–water nanofluids in a horizontal circular tube under a magnetic field. It was observed that a heat transfer enhancement of 15.43% was obtained by applying a magnetic field (200 G). Goharkhah et al. [14] analyzed heat transfer and pressure drop of Fe₃O₄–water nanofluid in a parallel plate channel under an alternating magnetic field. They observed that the maximum heat transfer enhancement of 37.34% was attained by application of alternating magnetic field. Asfer et al. [15] studied heat transfer characteristics of a magnetic nanofluid in a circular pipe. They found that increasing the gradient of the magnetic field improved heat transfer. Li and Xuan [16] studied the heat transfer characteristics of magnetic nanofluids exposed to a magnetic field. They concluded that applying a uniform magnetic field opposite to the flow direction reduced the heat transfer coefficient of the magnetic nanofluid.

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. Shahsavari et al. [17] investigated heat transfer in a heated pipe filled with a Fe_3O_4 -carbon nanotubes (CNTs) hybrid nanofluid. They concluded that 0.5 vol% Fe_3O_4 and 1.35 vol% CNTs hybrid nanofluid showed a maximum enhancement of 62.7% in the local Nusselt number, compared with water at $\text{Re}=2190$. Harandi et al. [18] analyzed the thermal conductivity of Fe_3O_4 -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 Fe_3O_4 -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 Fe_3O_4 -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. Nadooshan et al. [21] examined the viscosity of Fe_3O_4 -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 Fe_3O_4 -water and Fe_3O_4 -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, Fe_3O_4 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 Fe_3O_4 and CNTs are shown in Fig. 1. It is observed that the nanoparticle Fe_3O_4 has an average diameter of $15 \pm 5 \text{ nm}$.

The photographs of Fe_3O_4 -water and Fe_3O_4 -CNTs-water nanofluids are provided in Fig. 2. Carbon nanotubes (CNTs) were chemically functionalized by potassium persulfate solution with $\text{pH}=13$ 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. Fe_3O_4 magnetic nanoparticles and trisodium

Fig. 1 Images of two nanoparticles using TEM and SEM

Fig. 2 Real photographs of nanofluids

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 Fe_3O_4 -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% Fe_3O_4 -water and 1.32% Fe_3O_4 -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% Fe_3O_4 -water and 1.44% Fe_3O_4 -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% Fe_3O_4 -water and 1.44% Fe_3O_4 -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 Fe_3O_4 -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% Fe_3O_4 -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

Fe_3O_4 -water nanofluid and the deionized fluid are almost

Fig. 3 Zeta potential distributions**Table 1** Physical properties of the base fluid and nanoparticles at 25 °C

	$\rho/\text{kg m}^{-3}$	$C_p/\text{J kg}^{-1} \text{K}^{-1}$	$k/\text{W m}^{-1} \text{K}^{-1}$	$\mu/\text{Pa s}$
DI-water	997	4180	0.6 ± 0.012	0.0009
Fe_3O_4	5180	670	80	–
CNTs	2100	425	3000 [21]	–

constant with increasing shear rate, which indicates a Newtonian fluid behavior. For the Fe_3O_4 -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.

Fig. 4 Dynamic viscosity of various nanofluids as function of temperature (shear rate of 73.38 s^{-1})

Fig. 5 Dynamic viscosity of nanofluids as function of shear rate

Apparatus

Figure 6 shows a schematic and physical diagram of the experimental system, which consists of a pump, a flow

Fig. 6 The used experimental system

meter, a heat exchanger, a thermostatic bath, and a test section. The test section is a straight stainless steel pipe with a length of 1.2 m, an inner diameter of 3 mm, and an outer diameter of 4 mm. Wall temperature on the pipe is measured by nine T-type thermocouples with a diameter of 0.3 mm. The bulk temperatures at inlet and outlet of the test section are measured by two T-type armored thermocouples with a diameter of 1 mm. The temperature measurements of the mercury thermometer (accuracy of $0.1 \text{ }^{\circ}\text{C}$) are used to calibrate the thermocouples. Uncertainty of temperature measurements after calibration is $0.1 \text{ }^{\circ}\text{C}$. The thermocouple wires are directly welded on the test section to avoid any thermal resistance between thermocouples and test section. Temperature values are monitored by thermocouples connected to a 20-channel data acquisition unit. A constant heat flux for the pipe is supplied by a DC power of 0–150 W. The test section is wrapped with thermal insulation materials to minimize heat losses. A gear pump (WT3000-1JA) is used to circulate the nanofluid. In order to measure the flow rate, a turbine flowmeter of Titan 803 (Beijing Dongfang New Power Mechanical & Electrical Equipment Co., Ltd.) with a flow rate range of $0.05\text{--}0.5 \text{ L min}^{-1}$ is installed downstream the pump. The flowmeter is calibrated by weighing with a high-precision electronic balance. After calibration, the uncertainty of the flowmeter is 1%. A thermostatic bath maintains a constant inlet temperature of the fluid. A simple copper coil pipe cools down the outflow fluid downstream the test section.

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

Fig. 7 Dimensions of a cannula (mm)

Fig. 8 Three magnet arrangements

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_{rmax})	1.32 T
Maximum energy product (B_{Hmax})	42 MGOe
Relative permeability (μ_r)	1.05
Magnetic permeability of free space (μ_0)	$4\pi \times 10^{-7} \text{ N A}^{-2}$

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:

$$Nu = \frac{hD_i}{k} \quad (1)$$

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:

$$h = \frac{q''}{T_{w,i}(x) - T_b(x)} \quad (2)$$

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:

$$T_b(x) = \frac{q'' \pi D_o}{\rho Q C_p} x + T_{in} \quad (3)$$

where Q and ρ 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:

$$T_{w,i}(x) = T_{w,o}(x) - \frac{\alpha VI}{2\pi K_w L} \left[\frac{D_o^2}{D_o^2 - D_i^2} \log \left(\frac{D_o}{D_i} - 0.5 \right) \right] \quad (4)$$

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:

$$q'' = \frac{\alpha VI}{\pi D_o L} \quad (5)$$

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 α of the test section is calculated by:

$$\alpha = \frac{Q_m c_p (T_{in} - T_{out})}{VI} \quad (6)$$

where Q_m is the mass flow rate. The density ρ_{ff} , specific heat $C_{p,ff}$ and thermal conductivity k_{ff} of the hybrid nanofluid are calculated as shown in Ref. [23]:

$$\rho_{ff} = \varphi_1 \rho_1 + \varphi_2 \rho_2 + (1 - \varphi) \rho_{bf} \quad (7)$$

$$(\rho c_p)_{ff} = \varphi_1 (\rho c_p)_1 + \varphi_2 (\rho c_p)_2 + (1 - \varphi) (\rho c_p)_{bf} \quad (8)$$

$$\frac{k_{ff}}{k_{bf}} = \frac{\varphi_1 k_1 + \varphi_2 k_2 + 2\varphi k_{bf} + 2\varphi(\varphi_1 k_1 + \varphi_2 k_2) - 2\varphi^2 k_{bf}}{\varphi_1 k_1 + \varphi_2 k_2 + 2\varphi k_{bf} - \varphi(\varphi_1 k_1 + \varphi_2 k_2) + \varphi^2 k_{bf}} \quad (9)$$

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

$$\mu_{ff} = \mu_{bf}(1 + 2.5\varphi) \quad (10)$$

The total volume concentration (φ) of nanoparticles Fe_3O_4 and CNTs is obtained by:

$$\varphi = \varphi_1 + \varphi_2 \quad (11)$$

where subscripts 1, 2, p and bf represent physical properties of the Fe_3O_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 Nu (based on measurements of 9 thermocouples on the test section) and the increased value of the average Nu are introduced as

$$Nu_{avg} = \frac{\sum_{i=1}^9 Nu_i}{9} \quad (12)$$

$$\text{Max. } U_h = \pm \sqrt{(U_{C_p})^2 + (U_\rho)^2 + (U_Q)^2 + (U_{T_{out}-T_{in}})^2 + (U_{D_i})^2 + (U_L)^2 + (U_{T_w-T_b})^2} = \pm 8.99\% \quad (19)$$

$$\eta = \frac{Nu_{avg,ff} - Nu_{avg,bf}}{Nu_{avg,bf}} \quad (13)$$

Uncertainty analysis

Uncertainties of measurements are summarized in Table 3. The viscosity measurements (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

Table 3 Uncertainties of the measured variables

Variable name	Uncertainty
Voltage (V)	± 0.003509
Current (I)	$\pm 5.749 \times 10^{-4}$
Length (L)	$\pm 8.333 \times 10^{-4}$
Diameter (D_i)	± 0.03333
$T_{out} - T_{in}$	± 0.03497
$T_{w,i} - T_b$	± 0.07519
Dynamic viscosity	± 0.01
Volume flow (Q)	± 0.01

$$\text{Max. } U_R = \pm \sqrt{\left(\frac{s_1}{R} \frac{\partial R}{\partial s_1} U_{s_1}\right)^2 + \left(\frac{s_2}{R} \frac{\partial R}{\partial s_2} U_{s_2}\right)^2 + \dots + \left(\frac{s_n}{R} \frac{\partial R}{\partial s_n} U_{s_n}\right)^2} \quad (14)$$

where U_R is the maximum error of the parameter R . s is measurable parameter, and U_s is measured error. The maximum uncertainties of V , I , q , Re , h and Nu are determined by:

$$U_V = \pm \frac{0.1}{2.85} = \pm 0.03509 \quad (15)$$

$$U_I = \pm \frac{0.01}{18.25} = \pm 5.479 \times 10^{-4} \quad (16)$$

$$\text{Max. } U_q = \pm \sqrt{(U_I)^2 + (U_V)^2} = \pm 3.51\% \quad (17)$$

$$\text{Max. } U_{Re} = \pm \sqrt{(U_\rho)^2 + (U_Q)^2 + (U_{D_i})^2 + (U_\mu)^2} = \pm 3.62\% \quad (18)$$

$$\text{Max. } U_{Nu} = \pm \sqrt{(U_h)^2 + (U_{D_i})^2 + (U_k)^2} = \pm 9.59\% \quad (20)$$

Therefore, the uncertainties of q , Re , h and Nu are ± 3.51 , ± 3.62 , ± 8.99 , and $\pm 9.59\%$, respectively.

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]:

$$\vec{B} = \mu_0 \mu_r \vec{H} + \vec{B}_r \quad (21)$$

$$\vec{F}_M = V_p \frac{\chi_i}{\mu_0} \vec{B} \nabla \vec{B} \quad (22)$$

where H is the magnetic field, and B_r is the residual magnetic flux density. B is the magnetic flux density. μ_0 is the magnetic permeability of the free space, and μ_r is the relative permeability. V_p is the nanoparticle volume, and χ_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

Fig. 9 Comparison of simulated magnetic flux densities with results in Ref. [29]

Fig. 10 The details of geometry and grid

Fig. 11 Magnetic flux density distribution on cross plane (A–A) through pipe centerline for three cases

center line of the pipe are shown in Fig. 12. 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 3.68×10^{-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 3.63×10^{-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]:

$$Nu = \begin{cases} 1.302 \left(\frac{x/D_1}{Re Pr} \right)^{-1/3} - 0.5 & 0.00005 \leq \frac{x/D_1}{Re Pr} \leq 0.0015 \\ 4.364 + 0.263 \left(\frac{x/D_1}{Re Pr} \right)^{-0.506} e^{-41 \left(\frac{x/D_1}{Re Pr} \right)} & \frac{x/D_1}{Re Pr} > 0.0015 \end{cases} \quad (23)$$

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_3O_4 -water nanofluids and Fe_3O_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_3O_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_3O_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_3O_4 -water nanofluid.

Fe_3O_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_3O_4 -water nanofluids with three volume fractions (0.4, 0.8 and 1.2%) along the dimensionless x axial coordinate (x/D_1). For the 0.4 vol% Fe_3O_4 -water nanofluid, the local Nusselt number (Nu) reaches its maximum value nearly at

Fig. 12 Magnetic flux density components (B , B_x) and magnetic force (F_m) along the center line of the pipe for three cases

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

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

heat transfer enhancement is increasing with the increase of the number of magnets, Reynolds number and nanoparticle concentration.

For the 0.8 vol% Fe_3O_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_3O_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_3O_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_3O_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

Fig. 14 Average Nusselt numbers for magnetic nanofluids with various volume concentration and Reynolds numbers

Fig. 15 Variation of Nusselt number vs. dimensionless distance (X/D_i) for 0.4 vol% Fe_3O_4 –water nanofluid in three cases

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_3O_4 –CNTs–water nanofluid (1.2% Fe_3O_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_3O_4 –CNTs–water (1.2% Fe_3O_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 61.54%, respectively. For the 1.68 vol% Fe_3O_4 –CNTs–water (1.2% Fe_3O_4 + 0.48% CNTs) nanofluid at the same position, it is found that Nu of the hybrid

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.

As shown in Ref. [29], for the Fe_3O_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_3O_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_3O_4 –CNTs–water hybrid nanofluid is higher than for the Fe_3O_4 –water

Fig. 16 Variations of Nusselt number vs. dimensionless distance (X/D_i) for 0.8 vol% Fe_3O_4 -water nanofluid in three cases

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 Fe_3O_4 -water nanofluid, the increase in the number of cannulas results in an enhancement of heat transfer.

For the 1.32 vol% Fe_3O_4 -CNTs-water (1.2% Fe_3O_4 + 0.12% CNTs) nanofluid, the maximum enhancement of the local Nusselt number is higher than for 1.2 vol% Fe_3O_4 -water nanofluid in most cases. This result shows that adding a small amount of multi-walled carbon

nanotubes into the Fe_3O_4 -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% Fe_3O_4 -CNTs-water nanofluid is smaller than for the 1.2 vol% Fe_3O_4 -water nanofluid in all cases. The reason might be that the viscosity of the 1.68 vol% Fe_3O_4 -CNTs-water nanofluid under magnetic field is higher than that of 1.2 vol% Fe_3O_4 -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% Fe_3O_4 -CNTs-water (1.2% Fe_3O_4 + 0.24% CNTs)

Fig. 17 Variations of Nusselt number vs. dimensionless distance (X/D_i) for 1.2 vol% Fe_3O_4 –water nanofluid in three cases

hybrid nanofluid under a magnetic field (only exception for two cannula case at $\text{Re} = 996$).

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_3O_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_3O_4 –CNTs–water nanofluid with a single magnetic cannula (case I) by 26.6, 31.99 and 34.85% are found at $\text{Re} = 476$, 663 and 996, respectively. Compared with the 1.44 vol% Fe_3O_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_3O_4 -CNTs-water (1.2% Fe_3O_4 +0.12% CNTs) nanofluid in three cases

Fig. 19 Variations of Nusselt number vs. dimensionless distance (X/D_i) for 1.44 vol% Fe_3O_4 -CNTs-water (1.2% Fe_3O_4 +0.24% CNTs) nanofluid in three cases

Fig. 20 Variations of Nusselt number vs. dimensionless distance (X/D_i) for 1.68 vol% Fe_3O_4 -CNTs-water (1.2% Fe_3O_4 +0.48% CNTs) nanofluid in three cases

Table 4 Comparisons of the maximum Nusselt number for various nanofluids with and without magnetic field

	0.4% Fe_3O_4 /%	0.8% Fe_3O_4 /%	1.2% Fe_3O_4 /%	1.32% Fe_3O_4 + CNTs/%	1.44% Fe_3O_4 + CNTs/%	1.68% Fe_3O_4 + CNTs/%
Case I, Re = 446	20.57	27.82	38.3	39.97	42.57	33.24
Case II, Re = 446	27.91	31.68	45.46	47.21	48.24	35.91
Case III, Re = 446	31.16	33.78	51.21	52.57	54.21	45.67
Case I, Re = 663	28.48	30.45	38.24	37.6	43.11	33.07
Case II, Re = 663	34.05	36.1	51.02	51.09	53.72	47.05
Case III, Re = 663	34.93	42.58	55.01	56.64	58.61	52.67
Case I, Re = 996	27.55	33.16	39.81	41.66	45.57	32.79
Case II, Re = 996	36.55	37.36	53.73	54.52	54.51	48.74
Case III, Re = 996	47.04	42.85	61.13	59.86	61.54	56.88

Fig. 21 Nu enhancement of various magnetic nanofluids vs. Reynolds number and volume concentration

Conclusions

In this study, various volume fractions of nanoparticles Fe_3O_4 and carbon nanotubes (CNTs) were used to improve the thermophysical properties of the base fluid. Heat transfer characteristics of a Fe_3O_4 -CNTs-water hybrid nanofluid in a heated straight pipe were experimentally investigated and compared with Fe_3O_4 -water nanofluid

under magnetic field arrangement and for various Reynolds numbers.

For the 1.2 vol% Fe_3O_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 Fe_3O_4 -water nanofluid without magnetic field, the heat transfer performance can be significantly improved by increasing the number of magnetic cannulas. When 0.12% carbon nanotubes are added into 1.2%

Fe_3O_4 -water nanofluid, the maximum enhancement of the local Nusselt number is increased. Compared with cases under no magnetic field, a nanofluid with 1.2% Fe_3O_4 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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References

1. Ali HM, Ali H, Liaquat H, Maqsood HTB, Nadir MA. Experimental investigation of convective heat transfer augmentation for car radiator using ZnO-water nanofluids. *Energy*. 2015;84:317–24.
2. Sajid MU, Ali HM, Sufyan A, Rashid D, Zahid SU, Rehman WU. Experimental investigation of TiO_2 -water nanofluid flow and heat transfer inside wavy mini-channel heat sinks. *J Therm Anal Calorim*. 2019;137:1279–94.
3. Ebrahimi AE, Rikhtegar F, Sabaghan A, Roohi E. Heat transfer and entropy generation in a microchannel with longitudinal vortex generators using nanofluids. *Energy*. 2016;101:190–201.
4. Shanbedi M, Amiri A, Heris SZ, Eshghi H, Yarmand H. Effect of magnetic field on thermo-physical and hydrodynamic properties of different metals-decorated multi-walled carbon nanotubes-based water coolants in a closed conduit. *J Therm Anal Calorim*. 2018;131:1089–106.
5. Zheng D, Yang J, Wang J, Kabelac S, Sundén B. Analyses of thermal performance and pressure drop in a plate heat exchanger filled with ferrofluids under a magnetic field. *Fuel*. 2021;293:120432.
6. Kumar PCM, Chandrasekar M. Heat transfer and friction factor analysis of MWCNT nanofluids in double helically coiled tube heat exchanger. *J Therm Anal Calorim*. 2020. <https://doi.org/10.1007/s10973-020-09444-x>.
7. Dabiri E, Bahrami F, Mohammadzadeh S. Experimental investigation on turbulent convection heat transfer of SiC/W and MgO/W nanofluids in a circular tube under constant heat flux boundary condition. *J Therm Anal Calorim*. 2018;131:2243–59.
8. Sarafraz MM, Hormozi F, Nikkha V. Thermal performance of a counter-current double pipe heat exchanger working with COOH-CNT/water nanofluids. *Exp Therm Fluid Sci*. 2016;78:41–9.
9. Hosseini-pour E, Heris SZ, Shanbedi M. Experimental investigation of pressure drop and heat transfer performance of amino acid-functionalized MWCNT in the circular tube. *J Therm Anal Calorim*. 2016;124:205–14.
10. Shahsavari A, Godini A, Sardari PT, Toghray D, Salehipour H. Impact of variable fluid properties on forced convection of Fe_3O_4 /CNT/water hybrid nanofluid in a double-pipe mini-channel heat exchanger. *J Therm Anal Calorim*. 2019;137:1031–43.
11. Moreira LM, Carvalho EA, Bell MJV, Anjos V, Sant'Ana C, Alves APP, Fragneaud B, Sena LA, Archanjo BS, Achete CA. Thermo-optical properties of silver and gold nanofluids. *J Therm Anal Calorim*. 2013;114:557–64.
12. Wang J, Li G, Zhu H, Luo J, Sundén B. Experimental investigation on convective heat transfer of ferrofluids inside a pipe under various magnet orientations. *Int J Heat Mass Tran*. 2019;132:407–19.
13. Hosseini-zadeh M, Heris SZ, Beheshti A, Shanbedi M. Convective heat transfer and friction factor of aqueous Fe_3O_4 nanofluid flow under laminar regime. *J Therm Anal Calorim*. 2016;124:827–38.
14. Goharkhah M, Ashjaee M, Shahabadi M. Experimental investigation on convective heat transfer and hydrodynamic characteristics of magnetite nanofluid under the influence of an alternating magnetic field. *Int J Therm Sci*. 2016;99:113–24.
15. Asfer M, Mehta B, Kumar A, Khandekar S, Panigrahi PK. Effect of magnetic field on laminar convective heat transfer characteristics of ferrofluid flowing through a circular stainless steel tube. *Int J Heat Fluid Fl*. 2016;59:74–86.
16. Li Q, Xuan Y. Experimental investigation on heat transfer characteristics of magnetic fluid flow around a fine wire under the influence of an external magnetic field. *Exp Therm Fluid Sci*. 2009;33:591–6.
17. Shahsavari A, Saghaian M, Salimpour MR, Shafii MB. Experimental investigation on laminar forced convective heat transfer of ferrofluid loaded with carbon nanotubes under constant and alternating magnetic fields. *Exp Therm Fluid Sci*. 2016;76:1–11.
18. Harandi SS, Karimipour A, Afrand M, Akbari M, D'Orazio A. An experimental study on thermal conductivity of F-MWCNTs- Fe_3O_4 /EG hybrid nanofluid: effects of temperature and concentration. *Int Commun Heat Mass Tran*. 2016;76:171–7.
19. Askari S, Koolivand H, Pourkhalil M, Lotfi R, Rashidi A. Investigation of Fe_3O_4 /Graphene nanohybrid heat transfer properties: Experimental approach. *Int Commun Heat Mass Tran*. 2017;87:30–9.
20. Askari S, Lotfi R, Rashidi AM, Koolivand H, Koolivand-Salooki M. Rheological and thermophysical properties of ultra-stable kerosene-based Fe_3O_4 /Graphene nanofluids for energy conservation. *Energy Convers Manage*. 2016;128:134–44.
21. Nadooshan AA, Eshgarf H, Afrand M. Measuring the viscosity of Fe_3O_4 -MWCNTs/EG hybrid nanofluid for evaluation of thermal efficiency: Newtonian and non-Newtonian behavior. *J Mol Liq*. 2018;583:169–77.
22. Farbod M, Ahangarpour A. Improved thermal conductivity of Ag decorated carbon nanotubes water based nanofluids. *Phys Lett A*. 2016;380:4044–8.
23. Usman M, Hamid M, Zubair T, Haq RU, Wang W. Cu- Al_2O_3 /Water hybrid nanofluid through a permeable surface in the presence of nonlinear radiation and variable thermal conductivity via LSM. *Int J Heat Mass Tran*. 2018;126:1347–56.
24. Einstein A. Investigations on the theory of the Brownian movement. New York: Dover Publications; 1956.
25. Moffat RJ. Describing uncertainties in experimental results. *Exp Therm Fluid Sci*. 1988;1:3–17.
26. Pankhurst QA, Connolly J, Jones SK, Dobson J. Applications of magnetic nanoparticles in biomedicine. *J Phys D Appl Phys*. 2003;36:R167–81.

27. Azizian R, Doroodchi E, Mckrell T, Buongiorno J, Hu LW. Effect of magnetic field on laminar convective heat transfer of magnetite nanofluids. *Int J Heat Mass Tran*. 2014;68:94–109.
28. Lienhard IV, Lienhard V. A heat transfer textbook. 4th ed. Phlogiston Press; 2011.
29. Horton M, Hong H, Li C, Shi B, Peterson GP, Jin S. Magnetic alignment of Ni-coated single wall carbon nanotubes in heat transfer nanofluids. *J Appl Phys*. 2010;107:104320-1-104320-4.
30. Huang D, Wu Z, Sunden B. Effects of hybrid nanofluid mixture in plate heat exchangers. *Exp Therm Fluid Sci*. 2016;72:190–6.

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