Applied Thermal Engineering 126 (2017) 538–547

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Empirical analysis of heat transfer and friction factor of water/graphene oxide nanofluid flow in turbulent regime through an isothermal pipe

Ramin Ranjbarzadeh [a], Arash Karimipour [b,c,*], Masoud Afrand [a], Amir Homayoon Meghdadi Isfahani [b,c], Alireza Shirneshan [b,c]

[a] *Young Researchers and Elite Club, Najafabad Branch, Islamic Azad University, Najafabad, Iran*
[b] *Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran*
[c] *Modern Manufacturing Technologies Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran*

HIGHLIGHTS

- Investigation of water/graphene oxide nanofluid heat transfer and friction factor.
- Develop the experimental circular copper tube setup to include turbulent flow.
- 28% increase of thermal conductivity compared with the base fluid.
- 36.5% increase in convection coefficient compared with base fluid.
- Present nanofluid can be used in coolant systems like air heat exchangers.

ARTICLE INFO

Article history:
Received 27 November 2016
Revised 20 July 2017
Accepted 25 July 2017
Available online 27 July 2017

Keywords:
Experimental
Convective heat transfer
Pressure drop
Turbulent flow
Water/graphene oxide nanofluid

ABSTRACT

Nanofluid flow is considered one of the most important solutions for improving heat transfer systems. In this study, an isotherm heat transfer system has been designed and built in order to investigate the effect of utilizing water/graphene oxide nanofluid flow on heat transfer and the friction coefficient in a circular profile copper tube. The range of nanofluid concentration is considered as 0%, 0.025%, 0.05%, 0.075%, and 0.1% of volume fraction and Reynolds number of the turbulent flow is chosen between 5250 and 36,500. The nanofluid is made through a two-step method. The absolute value of Zeta potential equals 41 mV, which is measured experimentally and shows acceptable stability. The thermal conductivity of nanofluid has a maximum of 28% increase in comparison to the base fluid. Considering the experiential data from this study, the Nusselt number, the convective heat transfer coefficient, the pressure loss, the friction factor, and the coefficient of performance are investigated. In order to achieve validation, the results of this study are compared with former studies. Maximally, the nanofluid has a 40.3% augmentation in the convective heat transfer coefficient in comparison to the base fluid. In addition, a minor augmentation takes place during pressure loss and friction coefficient by utilizing the nanofluid that reaches a maximum of 16%. However, the thermal performance coefficient maximally increases by 1.148. According to the achieved results, the present nanofluid can be used in coolant systems like air cooling heat exchangers.

1. Introduction

Nowadays, heat transfer augmentation and amelioration are considered as the most important industrial subjects due to their dramatic effect on the growth and the efflorescence of industrial processes in connection with heat transfer systems or heat exchangers. On the other hand, the wide application of isothermal heat transfer systems in oil and gas industries, petrochemicals, and refineries makes their usage a significant issue and thereby necessitates the study of the improvement of such systems by researchers. Unique features of turbulent flow make it very useful [1]. Leonardo da Vinci was the first person to have worked on the numerical computation of turbulent flow [2]. Many numerical and empirical studies were thereafter conducted in this field [3–5].

The main reason to investigate the turbulence of the flow in heat transfer studies is due to the effect of the mixing on the conditions of the heat transfer process. Keeping this point in

---

* Corresponding author at: Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran.

E-mail address: arash.karimipour@yahoo.com (A. Karimipour).

http://dx.doi.org/10.1016/j.applthermaleng.2017.07.189
1359-4311/

Nomenclature

A	tube cross section area (m^2)
Cp	specific heat capacity (J kg^{-1} K^{-1})
D & d	diameter of the tube (m)
DW	distilled water
f	friction factor
g	gravity (N kg^{-1})
h	convective heat transfer coefficient (Wm^{-2} K^{-1})
k	thermal conductivity (Wm^{-1} K^{-1})
L	length of the tube (m)
$\dot{m}$	mass flow rate (kg s^{-1})
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature (K)
Q	volumetric flow (m^3 s^{-1})

Greek symbols

Δh	head loss (m)
ΔP	pressure difference (Pa or N m^{-2})
ΔT	temperature difference (K)
φ	volumetric concentration of nanoparticles (%)
φ_m	weight percentage (%)
η	thermal performance coefficient
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s or Ns m^{-2})
ζ	zeta potential

Super- and sub-scripts

bf	base fluid
in	inlet
LMTD	Log. mean temperature difference
nf	nanofluid
np	nanoparticles
out	outlet
w	wall

perspective, many researchers have been extensively studying heat transfer improvement in different fields [6,7].

The term 'nanofluid' was used by Choi in 1995 for the first time [8]. Owing to the superior heat transfer properties of nanofluids in comparison to base fluids, they are utilized in the method of deactivation [9]. The nanofluid supplied by the homogeneous scattering of nanoparticles smaller than 100 nm, in the base fluid, improves the mixing of the flow and leads to the enhancement of the heat transfer coefficient of the fluid. In addition to the positive effects in the problems related to energy issues, the optimal thermophysical properties of the nanofluids make them usable in order to be superseded instead of the conventional fluids in heat transfer systems. Such applications lead to the reduction of the heat exchanger's size, an increment of its efficiency, fuel consumption abatement, and cost saving [10,11].

The main features of nanofluids are higher convective heat transfer coefficient [12,13], high critical heat flux and boiling [14], and their proper storage of thermal energy [15,16]. As a consequence of the mentioned reasons, nanofluids have the potential to be the most suitable intelligent cooling fluid in the world [17].

According to the high heat transfer potential of carbon nanofluids, many studies were conducted in the field of carbon-based nanostructures including Carbon Nanotubes (CNTs) [18], graphite [19], graphene oxide [20], and graphene [21]. In the following paragraphs, the studies concerned heat transfer improvement using nanofluid will be presented:

Ebrahimian et al. [22] worked on the numerical and empirical study of the impacts of nanofluid utilization. They introduced the application of nanofluids on solar energy systems with the aim of heat transfer augmentation. In their study, the heat transfer coefficient increased by 21% while using nanofluids. Prasad et al. [23] investigated the effect of water/aluminum oxide nanofluid on the performance of a double pipe heat exchanger-containing twisted tape. They reported augmentations of 31.28% and 23% in the Nusselt number and the friction coefficient, respectively.

Yu et al. [24] studied the effect of the ethylene glycol/graphene oxide nanofluid on thermal conductivity. Using a nanofluid with 5% volume fraction, which has a heat transfer coefficient in the range of 4.9–6.9 W/m-K, the researchers reported an 86% increment in thermal conductivity.

Kamatchi et al. [25] empirically studied the reduced water/graphene oxide nanofluid. In their study, dynamic light scattering and zeta potential techniques were used to analyze the nanofluid stability. Thermal conductivity, viscosity, and the surface tension of the nanofluid depended on the concentration and the temperature of the nanofluid. The thermal conductivity of 0.3 g/L of nanofluid increased by 10% at a temperature of 75 °C. Kamatchi et al. showed that this nanofluid could be a suitable alternative for cooling liquids.

Hajjar et al. [26] empirically investigated the thermal conductivity of the graphene oxide nanofluid. There was a 47.5% augmentation in thermal conductivity for the nanofluid in a weight percent concentration of 0.25.

Amrollahi et al. [27] studied the convective heat transfer of the water/multilayer carbon nanotubes nanofluid flow in two different regimes, including the laminar and turbulent flow in a horizontal pipe and the constant heat flux boundary condition. According to their results, the convective heat transfer coefficient increased by a maximum of 40% when the nanofluid was at 0.25 wt%.

Sadeghinejad et al. [28] analyzed the heat transfer and the pressure loss of the water/graphene nanofluid flow in a double pipe heat exchanger with a constant heat flux boundary condition. The weight fraction of the nanofluid was 0.75–0.1%. There was a 13–160% augmentation in the convective heat transfer coefficient and the maximum thermal performance coefficient was 1.77. In another laboratory study, the water/graphene nanofluid convective heat transfer was investigated by Mehrali et al. [29]. They reported that the thermal performance coefficient of the nanofluid flowing in a horizontal pipe could reach 1.15.

Sadeghinejad et al. [30] analyzed the heat transfer improvement in a circular tube with the constant heat flux boundary condition in the presence of water/ graphene nanofluid flow in the turbulent regime, both numerically and empirically. They showed that the results that ensue from the numerical and the empirical studies had an acceptable overlap. Considering the different weight fractions, the Nusselt number showed positive changes in the range of 3–83%. Additionally, a 0.4–14.6% enhancement in pressure loss was reported as a consequence of the presence of nanoparticles.

Zeinali et al. [31] empirically investigated the force convective heat transfer of the water/aluminum oxide nanofluid flow inside a pipe having an isothermal wall. They reported an augmentation in the heat transfer coefficient that was much higher than the value predicted by the single phase heat transfer equation. They attributed such augmentation to scattering effects, the chaotic motion of the particles, Brownian motion, etc.

Hekmatipour et al. [32] studied the convective heat transfer compound (free and force convection) of the oil/copper oxide nanofluid in a horizontal pipe under the isothermal boundary condition of the wall. They showed that the heat transfer compound rate increases in a range of 0–1.5 up till 16% as a consequence of the increment in nanoparticle concentration. According to their reports, the maximum thermal performance coefficient was 1.16 in their study. Rakhsha et al. [33] empirically and numerically analyzed the convective heat transfer of the turbulent nanofluid flowing in a helically coiled tube. They used the Open-Foam software to analyze the problem and the results that ensued from the numerical study were in acceptable agreement with the empirical results. In their study, the Nusselt number increased by 17% in the maximum concentration of the nanofluid.

Naphon [34] studied the impact of the water/titanium oxide nanofluid flowing in a copper helically tube under the isothermal boundary condition for the wall. They showed that utilizing the nanofluid flow led to a 34.9% augmentation in the Nusselt number and the friction coefficient only faced minor changes.

Considering the studies on the effect of the nanofluid in the heat transfer processes mentioned in the literature review, it is clear that nanofluids have a dramatic effect on the augmentation of convective heat transfer. Hence, the present paper aims to design and construct the testing system of water/graphene oxide, and its supply and stabilization for the first time (to best knowledge of the authors). After that, the convective heat transfer of the nanofluid will be measured and it will be used as the main fluid in an isothermal heat transfer system. Considering the high potential of heat transfer in water/graphene nanoparticles, it is anticipated that the convective heat transfer coefficient will increase, which makes the nanoparticles a suitable choice for the improvement of the heat transfer process in different industries.

2. Experimental approach

2.1. Problem definition

This paper focuses on the empirical investigation of heat transfer and the friction factor of the water/graphene oxide nanofluid flow in different concentrations. The experiments are performed in the designed system for the test and the boundary condition of the problem is considered isothermal. The fluid flow, with different concentrations at an ambient temperature, enters into the copper pipe. The scope of the Reynolds number is between 5250 and 36,500. Owing to the heat transfer between the nanofluid and isothermal wall, the nanofluid temperature increases. In this study, the water/graphene oxide nanofluid is used for the first time with the aim of heat transfer improvement. By the designed testing system and through the utilization of the water/graphene oxide nanofluid as a high heat transfer potential nanofluid, the changes of the convective heat transfer coefficient, Nusselt number, pressure loss, friction factor, and the thermal performance coefficient are investigated.

The governing parameters in the current study include the Reynolds number of the inner fluid and the volume concentrations of water/graphene oxide nanofluid which equal 0%, 0.025%, 0.075%, and 0.1%. The present experimental setup can represent a coolant system alike the air cooling heat exchanger. The results are included the inlet and the outlet temperatures of the nanofluid flowing in the copper pipe, the pipe surface temperature at different intervals, the flow rate, and the physical properties of the apparatus system.

2.2. Apparatus system

In order to study the water/graphene oxide nanofluid flow, heat transfer, and friction coefficient in a copper pipe possessing the isothermal boundary condition, a system is designed (shown in Fig. 1). The experiment system contains a fluid flow closed circuit that consists of different parts such as a nanofluid reservoir tank, a TAIFU electro pump (model: GRS25/6), a glass rotameter, a copper tube with an internal diameter equal to 8.5 mm and an outer diameter equal to 10mm, a differential pressure gauge (model: PM-9102), a K-type thermocouple with a display, four 2000 W heating elements to vaporize the water in the test zone and a way-back circuit to control the fluid flow rate, and a plumbing system. It should be noted that the temperature steady-state period to record the experimental data is about 15 min and the experiments are repeated at least two times to ensure that there is no reproducibility of experimental error

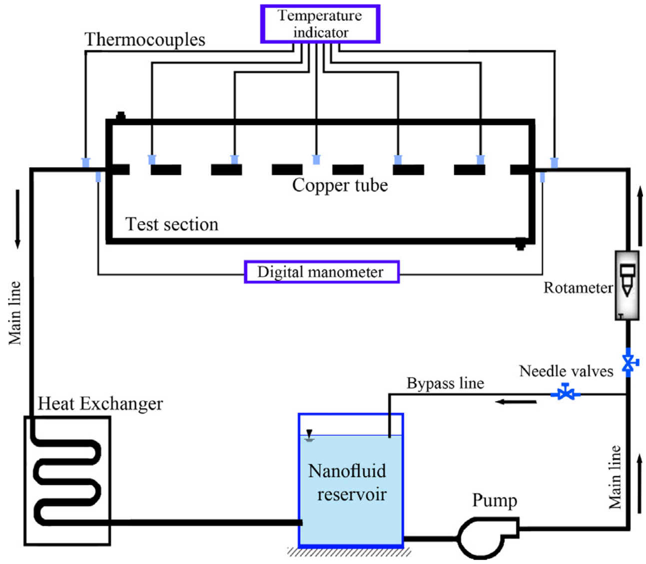


Fig. 1. The schematic of the apparatus system.

2.3. Water/graphene oxide supply, stabilization, and properties

The process of nanofluid preparation plays a paramount role in the quality of scattered nanoparticles in the base fluid. In addition, nanoparticles agglomeration is an important factor in the supply process of nanofluids [35,36]. Providing a stable nanofluid is a fundamental challenge in the path of nanofluid utilization [37]. The agglomerates formed by Van der Waals interactions in nanoparticles lead to a change in thermophysical properties of the nanofluid [38,39].

In this study, graphene oxide nanoparticles with OH and COOH functional groups are used. The graphene oxide nanoparticles have some special properties like high convective heat transfer, high special surface, hydrophilicity, insolubility, and low density. The properties of the used nanosheets produced by the US Research Nanomaterials, Inc. are represented in Table 1. To examine the properties of the supplied nanoparticles, the Scanning Electron

Table 1
Thermo-physical properties of graphene oxide nanoplatelets.

Thermo-physical property	Value
Appearance/morphology	Black powder/nanoplatelets
Diameter (μm)	2
Purity (%)	99
Density (g/cm^3)	1
Thickness (nm)	3.4–7 nm with 6–10 Layers
Specific surface area (m^2/g)	100–300

Microscope and X-ray diffraction are used; the results are shown in Fig. 2.

The nanoparticles are produced in a two-step method including three different processes; these are: the chemical, the magnetic, and the ultrasonic process. Through the addition of the nanoparticles to pure water, which is the base fluid, using the mentioned processes, the nanofluid will be produced. To weigh the nanoparticles, an AND GR200 digital balance with 0.0001 g precision, is used. After preparing the base fluid with a suitable pH, the nanoparticles will be mixed with the base fluid using a RET magnetic stirrer. After that, by using the ultrasonic equipment, the nanoparticles go under the ultrasonic waves for 4.5 h. The model of the ultrasonic bath is the PARSONIC 30S with 400 W power and a frequency equal to 28 kHz. Fig. 4 shows the images of the nanofluid samples.

The produced nanofluid apparently showed three months of stability. To analyze its stability, the sedimentation photograph-capturing method was used as the first step. To have a more accurate analysis, the zeta potential test was used. This test was conducted by using the Nano ZS (red badge) ZEN 3600 DLS equipment.

3. Governing equations, validation, and uncertainty

3.1. Governing equations

Calculation of the Nusselt number and the changes in the convective heat transfer coefficient is an effective method to assess the thermal performance of an isothermal boundary condition heat transfer system. To assess the convective heat transfer coefficient of the nanofluid flow, Eq. (1) is used as follows:

$$h = \frac{\rho Q C_p (T_{out} - T_{in})}{\pi D L \Delta T_{LMTD}} \tag{1}$$

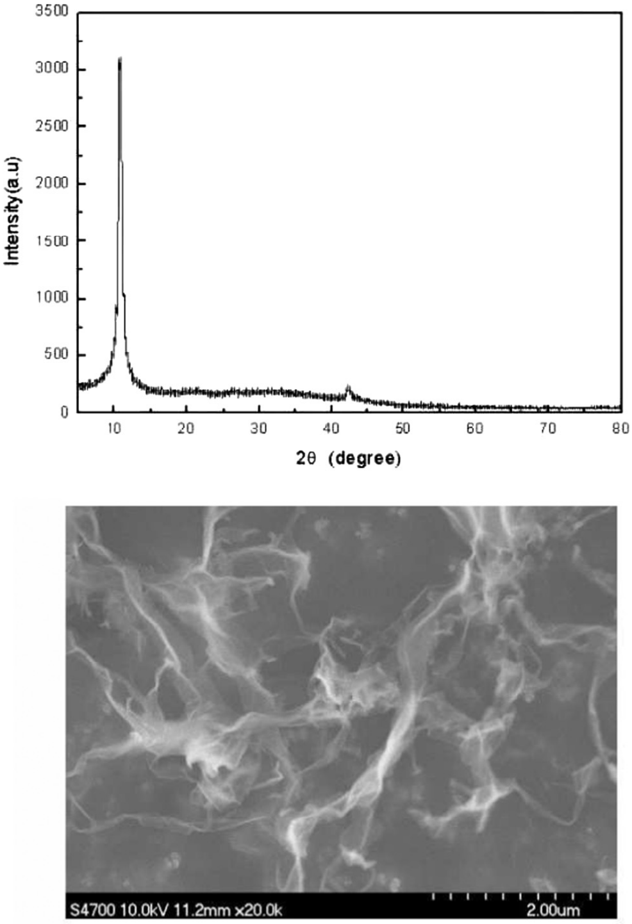


Fig. 2. The images of SEM and X-ray diffraction tests on the graphene oxide nanoparticles.

The values of the ρ, C_p, and μ of the nanofluid should be calculated by empirical equations presented by Pak and Cho [40] (Eqs. (2) and (3)) or the empirical equation presented by Ijam et al. [41] (Eq. (4)). In addition, the convective heat transfer coefficient of the nanofluid should be measured.

$$\rho_{nf} = \varphi \rho_{np} + (1 - \varphi) \rho_{bf} \tag{2}$$

$$C_{P,nf} = \varphi C_{p,np} + (1 - \varphi) C_{p,bf} \tag{3}$$

$$\mu_{nf} = \mu_{bf} (1 + 343 \varphi_m) \tag{4}$$

In order to calculate ΔT_{LMTD} and T_s Eqs. (5) and (6) are used as follows:

$$\Delta T_{LMTD} = \frac{T_{out} - T_{in}}{Ln((T_s - T_{in})/(T_s - T_{out}))} \tag{5}$$

$$T_S = \frac{(T_1 + T_2 + T_3 + T_4 + T_5)}{6} \tag{6}$$

The logarithmic nature of these temperature differences refer to the exponential nature of the temperature reduction inside the pipe [42].

Moreover, to calculate the Nusselt number and the Prandtl number, Eqs. (7) and (8) are applied:

$$Nu = \frac{hD}{k} \tag{7}$$

$$Pr = \frac{c_p \mu}{k} \tag{8}$$

It is essential to measure the pressure loss of nanofluid flow in addition to the heat transfer measurement due to the effect of pressure loss on the application of heat transfer systems in industrial units. The inlet and the outlet pressure differences are measured by the differential pressure gauge and it is shown as the height difference in the gauge. Generally, the Darcy–Weisbach relation (Eq. (9)) is used to assess the friction factor of the incompressible fluid flow in a direct pipe and the pressure loss should be calculated by Eq. (10).

$$f = \frac{\Delta p}{\left(\frac{L}{d}\right) \rho \frac{v^2}{2}} = \frac{\pi^2 \rho \Delta p d^2}{8 \dot{m}^2 L} \tag{9}$$

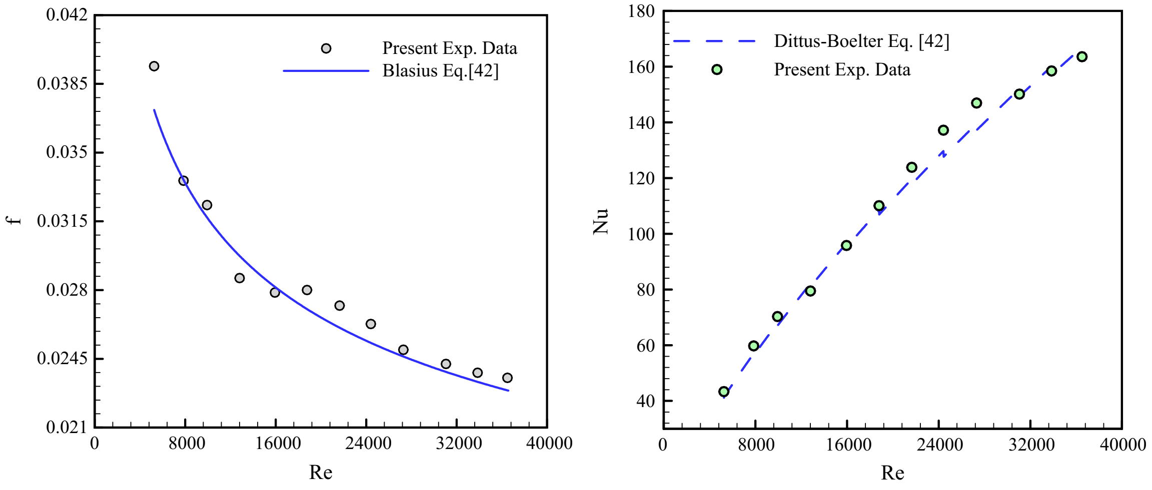
$$\Delta P = \rho . g . \Delta h \tag{10}$$

Thermal performance coefficient [32] which indicates Nusselt number over friction factor in the case of using nanofluid instead of the base fluid is presented in Eq. (11) as follows:

$$\eta = \frac{\frac{Nu_{nf}}{Nu_{bf}}}{\left(\frac{f_{nf}}{f_{bf}}\right)^{\frac{1}{3}}} \tag{11}$$

3.2. System performance, validation, and uncertainty

An experiment with pure water initially was performed to validate the experiment system and the empirical results. The date ensues from the pure water experiment in comparison to the results of the previous studies. Eq. (12), which is called the Blasius equation, is used to assess the hydrodynamic performance of the flow and the thermal performance of the flow in the range of the



(a) (b)

Fig. 3. Validation for pure water using the Reynolds number; (a) friction factor and (b) Nusselt number.

Table 2
The range and accuracy of the measuring instruments.

Description	No.	Model	Range	Accuracy
Surface temperature	5	Type K thermocouple	−40 to 300 (°C)	0.5 (°C)
Temp. of in and out flow	2	RTD (PT-100) sensor	0–100 (°C)	0.1 (°C)
Fluid flow rate	1	LZB 80	1–10 (m^3/h)	2.5% F.S.
Fluid pressure drop	1	Model: PM-9102	0–200 (mbar)	2% F.S.

Table 3
The uncertainty of the experimental data.

Parameters	Uncertainty (%)
Experimental heat transfer coefficient	5.3
Nusselt number	5.8
Friction factor	4.1
Pressure drop	2.4

mentioned Reynolds number, which is assessed with Eq. (13) and is called the Dittus–Boelter equation [42]:

$$f = 0.3164Re^{-0.25} \qquad (12)$$

$$Nu = 0.023Re^{0.8}Pr^{0.4} \qquad (13)$$

It should be assumed that Eq. (12) is limited to the turbulent flow and the limitations of Eq. (13) are illustrated as $\frac{l}{d} \geqslant 10, 0.6 < Pr < 100 \text{ and } 2500 < Re < 1.25 \times 10^5$.

Different experiments are designed in the range of $5250 \leqslant Re \leqslant 36,500$.

Fig. 3(a) shows the friction factor inside the pipe in the range of turbulent flow validation. It is seen that there is a strong accordance between the Blasius equation and the empirical results. There is a maximum error of 6.2%. In addition, the Nusselt number of pure water validation is shown in Fig. 3(b), which implies that the maximum error is 5.8%.

Moreover, and according to the diffusion theory proposed by Moffat et al. [43], the effect of each equipment error (shown in Table 2) on uncertainty is studied and then presented in Table 3.

4. Results and discussion

The results of nanofluid stability, pressure loss, the friction coefficient, thermal conductivity, and the Nusselt number are presented in this section. Moreover, the impact of the governing parameters will be discussed.

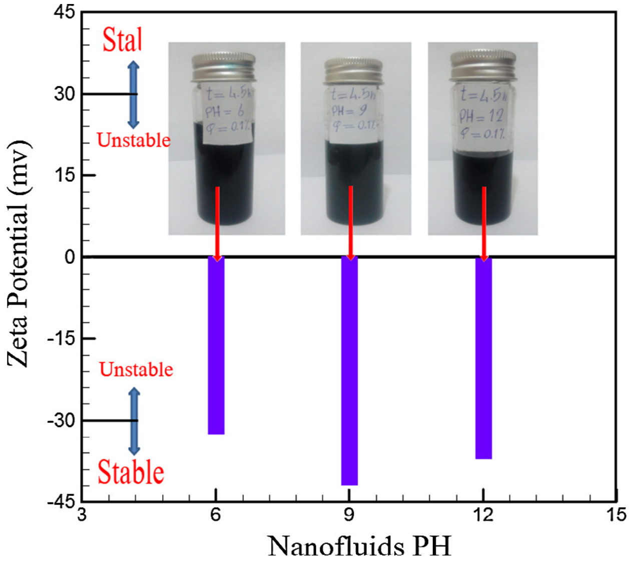


Fig. 4. Zeta potential test of nanofluid stability in different pH values.

4.1. Nanofluid stability and thermophysical properties

After the studies and tests were carried out, water/graphene oxide nanofluid with long-term stability was supplied. To assess the stability of the nanofluid, the zeta potential test was used and the results are presented in Fig. 4.

The absolute values of the zeta potential test of the nanofluid would seem to suggest that there is an eligible stability at a pH value = 9. The absolute value at this pH is $\|\zeta\| = 41$. Long-term stability leads to stability in the thermophysical properties of the nanofluid. The main reasons behind nanofluid stability can be classified into choosing the optimal pH (defined experimentally in the present study), the presence of functional groups in graphene oxide, and the absence of density difference between the base fluid and nanoparticles, respectively.

Thermal conductivity, which is the most important parameter in the heat transfer augmentation of the nanofluid, is empirically measured at different temperatures and different volume fractions. There was a maximum enhancement of 28% in thermal conductivity. The nanofluid properties should be uniformly defined in every case. Table 4 presents the full range of properties.

4.2. Nanofluid pressure loss and friction factor

The Reynolds number range in this study was chosen between 5250 and 36,500. Considering the high potential of heat transfer in the mentioned nanofluid, an accurate and comprehensive analysis of pressure loss is necessary in order to identify its applications. The results of the pressure loss analysis for different pipe lengths and friction coefficients of the water/graphene oxide nanofluid flow in 0.025%, 0.05%, 0.075%, and 0.1% volume concentrations are depicted in Fig. 5 and Fig. 6. A greater Reynolds number corresponds to a larger amount of pressure loss; however, this event occurs more severely at higher values of Re and higher volume percentages. Moreover, the inverse effect of the Reynolds number on the friction coefficient can be accurately traced in Fig. 6; Fig. 6 also implies the more important role of volume percent at higher values of *Re*. It is apparent that the dynamic viscosity increases as a consequence of nanoparticles augmentation in the base fluid. In addition to the physical nature of pressure loss, changes in the effect of flow velocity increase; the changes of the dynamic viscosity of nanofluid as an effect of nanoparticle augmentation are known as another important parameter in pressure loss. It should be noted that the pressure loss increases with the increment of concentration.

There is a reverse relation between the friction coefficient and the pressure loss changes. The reason for such a reverse relation is related to the relationship between pressure loss and flow velocity. As previously mention, Fig. 6 demonstrates the results of the nanofluid flow friction factor. On the basis of the data represented in Fig. 6, the friction coefficient of the nanofluid could increase by a maximum of 16% in comparison to the base fluid. The maximum difference of the nanofluid and the base fluid friction coefficient is negligible in comparison to other studies. That could be related to flow mixing, which corresponds to ignoring the particle turbulences against the flow.

Fig. 7 displays the variation of the friction factor ratio, i.e., the greater the Reynolds number, the greater the friction factor. At the maximum level, the friction factor of the nanofluid can increase to 16 in relation to pure water. The main reason behind the variations of friction factor is the relationship between pressure drop

Table 4
The full range of water/graphene oxide nanofluid properties observed in all the tests.

Nanofluid properties	Unit	Range
Volumetric concentration of nanoparticles	%	$0 \sim 0.1$
Thermal conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$	$0.623 \sim 0.816$
Density	$\mathrm{kg\,m^{-3}}$	$985.7 \sim 994.906$
Dynamic viscosity	pa s	$5.13 \times 10^{-4} \sim 9.146 \times 10^{-4}$
Specific heat capacity	$\mathrm{J\,kg^{-1}\,K^{-1}}$	$4170.5 \sim 4179$

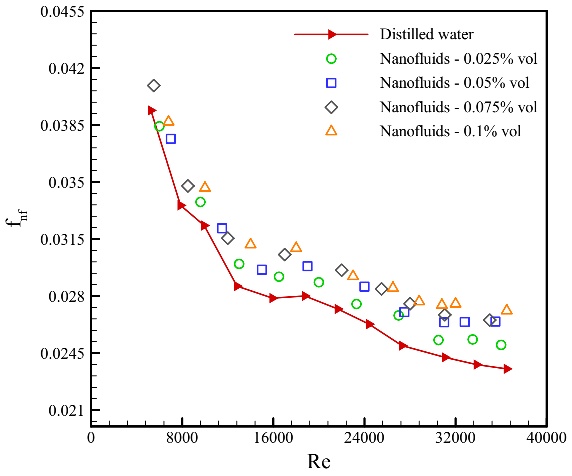


Fig. 6. The variations of nanofluid friction factor for different Reynolds numbers at different concentrations.

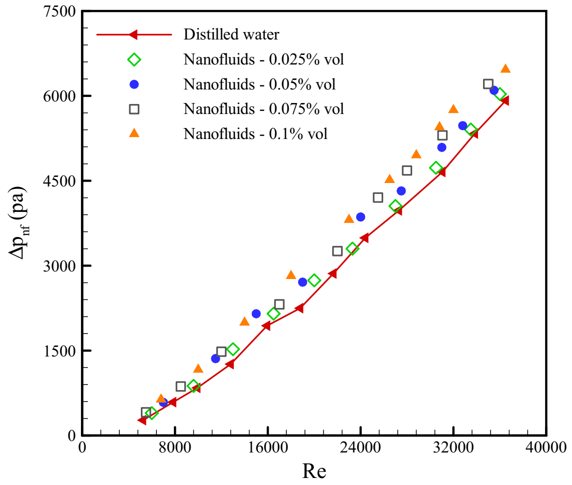


Fig. 5. The changes in pressure loss of the nanofluid flow for different Reynolds numbers in various concentrations.

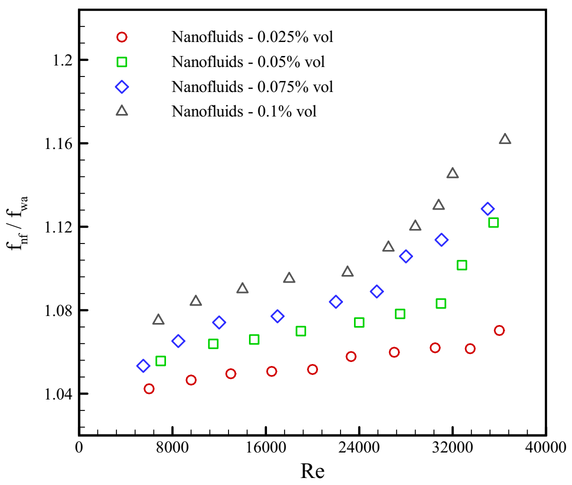


Fig. 7. Water/graphene oxide nanofluid to base fluid friction factor ratio for different Reynolds numbers.

and the friction factor as well as the simultaneous increase in the pressure drop with Reynolds number.

4.3. Variations effects of copper pipe surface temperature

The results of the pipe surface temperature are depicted in Fig. 8. The effect of surface temperature abatement ensues from the presence of much greater nanofluid changes at high concentrations. Furthermore, the temperature decreases as the Reynolds number increases.

The thermal energy transfer to the nanofluid in the presence of nanoparticles is the reason for such surface temperature reduction. As the particles collide with the pipe wall, they absorb thermal energy, and as a consequence, the surface temperature decreases. The surface temperature reduction is according to the results presented in the references of [44,45].

4.4. Convective heat transfer coefficient and Nusselt number

Flow turbulences made by a greater Reynolds number and the desired high-potential thermal properties of nanofluid could be the main reasons behind higher heat transfer rates. The Reynolds number enhancement leads to more turbulence; as a result, the Nusselt number and the convective heat transfer coefficient increases. This occurs due to a reduction in the boundary layer thickness and the dramatic augmentation of the temperature gradient [39].

As observable from Fig. 9, with an increment in the Reynolds number, and consequently, the increment of the erratic movement of nanoparticles in the base fluid leads to the augmentation of the convective heat transfer coefficient. It is noteworthy to say that such augmentation will be more remarkable at higher concentrations.

Adding nanoparticles to the base fluid leads to the changes in the structure of flow from one single phase flow to biphasic flow. Additionally, the convective heat transfer coefficient of nanofluid increases by 40.3% through the addition of graphene oxide nanosheets. The presence of the nanofluids in the locality of the wall has a much greater effect on the energy exchange rate. Subsequently, the heat transfer between the fluid and the wall will be dramatically augmented. In addition, in the high flow rates, dispersion effects and erratic movements, and finally, nanoparticles distribution in fluid will intensify and lead to more heat transfer in the heat exchange system. As a result, the temperature profile will be flatter and the flow will tend to be more turbulent in comparison to pure water.

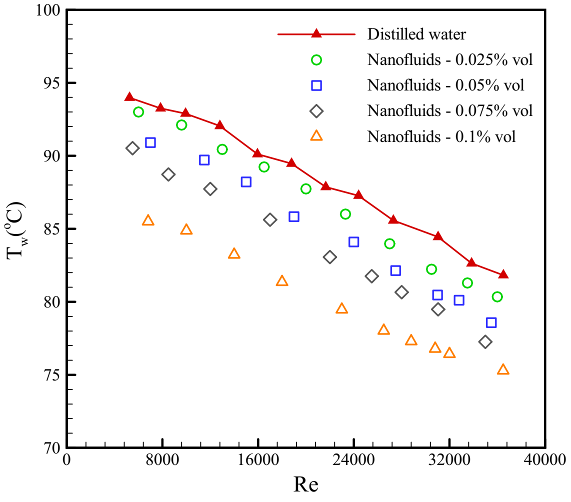


Fig. 8. Pipe surface temperature for different Reynolds numbers.

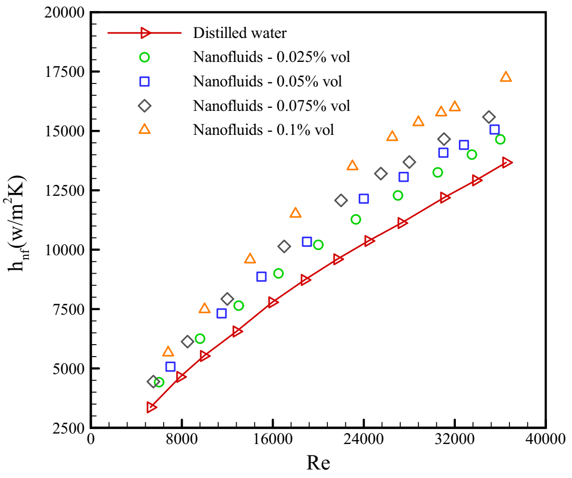


Fig. 9. Convective heat transfer coefficient of nanofluid in different Reynolds numbers.

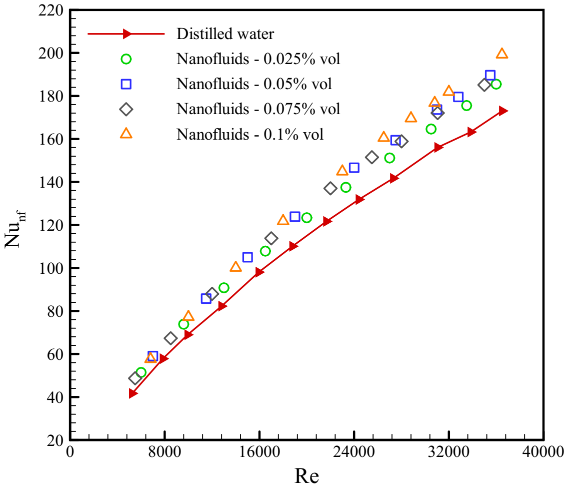


Fig. 10. The variations of nanofluid Nusselt number at different Reynolds numbers and concentrations.

In Fig. 10, the results of the nanofluid Nusselt number for different concentrations are presented. There is a 17.6% augmentation in the Nusselt number for 0.1% concentration, which is the maximum augmentation. Considering the fact that the velocity of the flow in experiment pipe is less when the flow rate is low in comparison to the time at which the flow rate is high, it can be concluded that with the increment of the nanofluid temperature, the volume fraction and the convective heat transfer increases as a consequence of wall temperature. These facts are very effective in calculating Nusselt number related to Eq. (7).

According to Fig. 11, it is clear that there is an augmentation thermal conductivity in the presence of nanoparticles. Utilizing the nanofluid in low Reynolds numbers leads to a higher convective heat transfer coefficient; the reason behind such event can be the low velocity of flow at this state.

4.5. Thermal performance coefficient of the nanofluid

Utilization nanofluid leads to a dramatic increment in heat transfer and the friction coefficient of the nanofluid is augmented

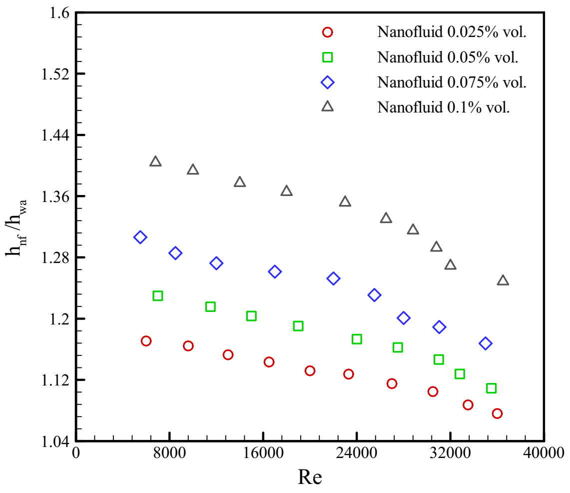


Fig. 11. Nanofluid to pure water convective heat transfer coefficient ratio for different Reynolds numbers.

in comparison to the base fluid. Thus, a reasonable response could be achieved by assessing the thermal performance coefficient, which involves the thermal and hydrodynamic analysis of flow (see Fig. 12).

As well established, the thermal performance coefficient indicates the heat transfer gain arising from nanofluid flow over the undesired pressure loss. The maximum value of the thermal performance coefficient is achieved at 0.1 vol% of nanofluid in low Reynolds numbers, equal to 1.148.

4.6. Comparison of the experimental results against other studies

The thermal performance index evaluates the variations in heat transfer and the pressure drop of nanofluid flow in a thermal system. Fig. 13 displays the comparison of the results of coefficient of thermal performance in this study against the results obtained by other researchers in Refs. [46,47].

According to the results provided in Fig. 13, it is always beneficial to adopt the nanofluid flow within the range of Reynolds numbers, where the coefficient of thermal performance in all scenarios is greater than 1.

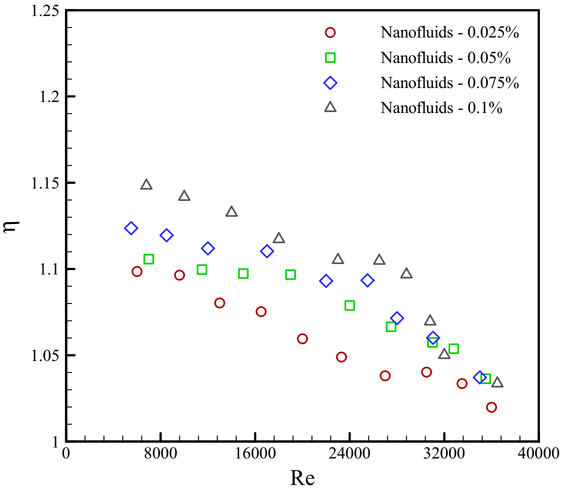


Fig. 12. Thermal performance coefficient for different Reynolds numbers.

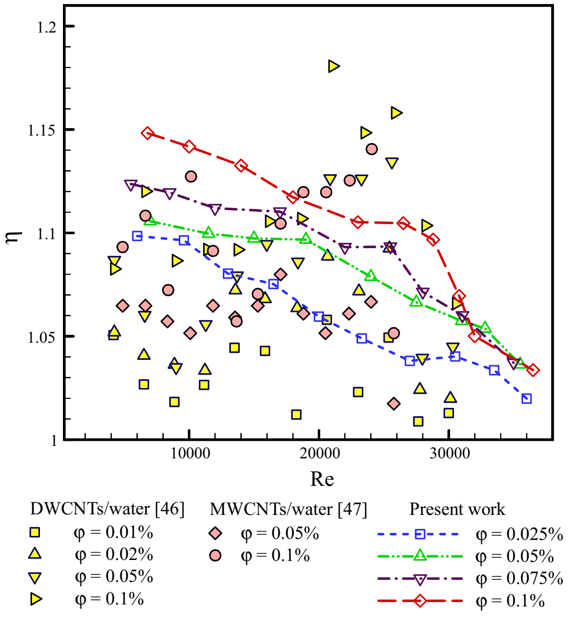


Fig. 13. Comparison of the results on the coefficient of thermal performance in this study against the results obtained by other researchers in Refs. [46,47].

A comparative overview of the coefficient of thermal performance in this study and previous studies (Fig. 13) revealed that the adoption of the nanofluid flow coefficient is more desirable with regard to the results of thermal performance at lower Reynolds numbers. Such variations can be attributed to the simultaneous increase in the friction factor for nanofluid flow and the Nusselt number (heat transfer coefficient) with increasing Reynolds numbers for nanofluids. The results of incremental variations in the friction factor and the Nusselt number have been displayed in Figs. 6 and 10, respectively.

Fig. 14 shows that the convective heat transfer coefficient has always increased for different concentrations of the nanofluid. Such variations suggest that nanofluids are more favorable than base fluids as alternatives in thermal systems.

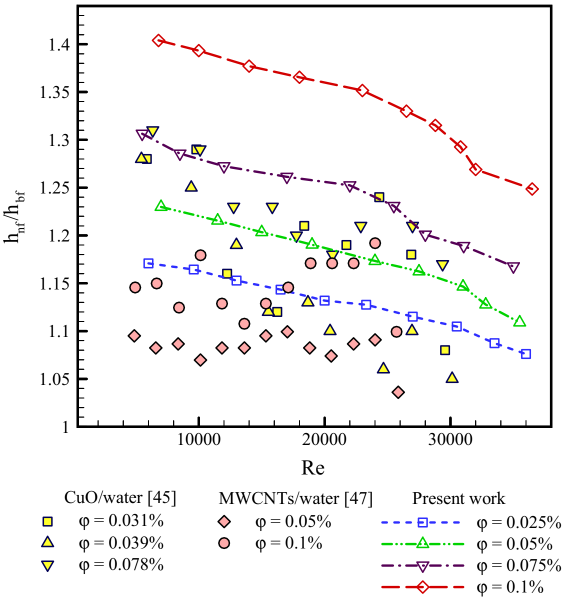


Fig. 14. Comparison of the variation in the heat transfer coefficient of displacement for nanofluids with those of [45,47].

Table 5
Comparison of experimental results obtained in this study against the results observed in other studies.

No.	Experimental condition	Nanofluid	Reynolds number range	Heat transfer coefficient enhancement (%)	Fiction factor augmentation (%)
1	Present work	Graphene oxide/water	5250–36,500	40.3	16
2	Tube under a constant wall temperature [48]	Alumina/water	5180–32,900	48	–
3	Tube under a constant heat flux [30]	Graphene/water	4583–18,187	83	17.2
4	Shell and tube heat exchanger [49]	Graphene/water	1920	35.6	–
5	Tube under a constant heat flux [50]	Functionalized graphene/ water	5000–17,500	19.68	9.22
6	Tube under a constant heat flux [27]	FMWNT/water	4583–18,187	40	Slight changed

In the current study, the nanofluid flow of water/graphene oxide indicated that the heat transfer coefficient had significantly increased. Meanwhile, there was a rising trend of variations in the heat transfer coefficient observed at various concentrations and Reynolds numbers. Nevertheless, the comparison of variations in the convective heat transfer coefficient for nanofluids against base fluids (Fig. 14) revealed a decline in the variation gradient. Such trends overlap with the results of other studies (copper oxide and carbon nanotubes). On the other hand, the heat transfer coefficient in this study showed far greater improvement in comparison to previous studies (copper oxide and carbon nanotubes). These results could a consequence of the high capacity for heat transfer in graphene oxide nanosheets. Defining the experimental conditions in this study and the previous works, Table 5 compares the results regarding the heat transfer coefficient of nanofluids in heat transfer systems; good agreements are observable.

5. Conclusion

In recent years, many researchers have focused on heat transfer improvement due to its basic applications in different industries. Utilization of nanofluid with a high potential for heat transfer is one of the most important methods that is at the center of attention for many researchers. The foregoing study has attempted to analyze the heat transfer and the friction factor of water/graphene oxide nanofluid flow inside an isothermal copper pipe. According to the achieved results, the present nanofluid can be used in coolant systems like air cooling heat exchangers.

The conclusions that are drawn from the points mentioned in the article are listed in the following paragraphs:

- From the zeta potential test ($\|\zeta\| = 41\,mv$), a desired stability is reached at pH value = 9, and the supplied nanofluid retains its stability for a long period. Such mentioned stability could be a result of the uniform dispersion of nanoparticles in the base fluid, the desired pH value of the base fluid, the presence of functional groups in graphene oxide nanoparticles, the nano-dimensions of the particles, and the absence of the density difference in the base fluid.
- There was a 28% augmentation in thermal conductivity in the presence of the nanofluid due to its superior heat transfer potential; this rate is greater than the rate that was reported in the previous articles concerned with nanofluids.
- According to the analysis of the hydrodynamic behavior of flow inside the pipe, it can be seen that the pressure loss increased as the Reynolds number is augmented. On the other hand, the friction coefficient follows a reverse process with the increment of the Reynolds number.
- The change in the trend of the nanofluid friction factor with a change in the Reynolds number is almost the same as pure water. The nanofluid friction factor increases by a maximum of 16% in comparison to pure water.
- Owing to the properties and the high potential for heat transfer in nanofluids, the utilization of nanofluids leads to surface temperature reduction in comparison to the base fluid.
- The changes in the heat transfer coefficient are positive when the Reynolds number increases from 5250 to 36,500. The heat transfer coefficient and the friction coefficient increase by 40.3% and 16%, respectively, in their maximum augmentation. According to these results, it can be concluded that the nanofluid shows a significantly higher performance.
- The maximum increment in the convective heat transfer coefficient ratio occurs at low Reynolds numbers. It is clear that this ratio decreases with the increment of the Reynolds number. This shows that the utilization of the nanofluid is much more appropriate for efficiency at low Reynolds numbers.
- The thermal performance coefficient could reach 1.148; therefore, the utilization of the present nanofluid as the heat transfer fluid at similar conditions of the supposed experiment can be an effective way to improve the system's thermal performance.

References

[1] N.A.C. Sidik et al., The significant effect of turbulence characteristics on heat transfer enhancement using nanofluids: a comprehensive review, Int. Commun. Heat Mass Transfer 72 (2016) 39–47.
[2] B.E. Launder, D. Spalding, The numerical computation of turbulent flows, Comput. Meth. Appl. Mech. Eng. 3 (2) (1974) 269–289.
[3] A. Najafi et al., Numerical analysis of turbulent swirling decay pipe flow, Int. Commun. Heat Mass Transfer 32 (5) (2005) 627–638.
[4] A. Karimipour, M.H. Esfe, M.R. Safaei, D.T. Semiromi, S. Jafari, S.N. Kazi, Mixed convection of copper–water nanofluid in a shallow inclined lid driven cavity using the lattice Boltzmann method, Physica A 402 (2014) 150–168.
[5] A. Karimipour, A.H. Nezhad, A. D'Orazio, M.H. Esfe, M.R. Safaei, E. Shirani, Simulation of copper–water nanofluid in a microchannel in slip flow regime using the lattice Boltzmann method, Eur. J. Mech.-B/Fluids 49 (2015) 89–99.
[6] M. Bhuiya et al., Heat transfer and friction factor characteristics in turbulent flow through a tube fitted with perforated twisted tape inserts, Int. Commun. Heat Mass Transfer 46 (2013) 49–57.
[7] M. Parsazadeh, H. Mohammed, F. Fathinia, Influence of nanofluid on turbulent forced convective flow in a channel with detached rib-arrays, Int. Commun. Heat Mass Transfer 46 (2013) 97–105.
[8] S. Chol, Enhancing thermal conductivity of fluids with nanoparticles, ASME-Publicat.-Fed 231 (1995) 99–106.
[9] A. Bergles, Some perspectives on enhanced heat transfer—second-generation heat transfer technology, J. Heat Transfer 110 (4b) (1988) 1082–1096.
[10] M. Afrand, Experimental study on thermal conductivity of ethylene glycol containing hybrid nano-additives and development of a new correlation, Appl. Therm. Eng. 110 (2017) 1111–1119.
[11] A. Andreozzi et al., Forced convection enhancement in channels with transversal ribs and nanofluids, Appl. Therm. Eng. 98 (2016) 1044–1053.
[12] M. Heyhat et al., Experimental investigation of laminar convective heat transfer and pressure drop of water-based Al_2O_3 nanofluids in fully developed flow regime, Exp. Thermal Fluid Sci. 44 (2013) 483–489.
[13] A. Naghash, S. Sattari, A. Rashidi, Experimental assessment of convective heat transfer coefficient enhancement of nanofluids prepared from high surface area nanoporous graphene, Int. Commun. Heat Mass Transfer 78 (2016) 127–134.
[14] S.W. Lee, K.M. Kim, I.C. Bang, Study on flow boiling critical heat flux enhancement of graphene oxide/water nanofluid, Int. J. Heat Mass Transfer 65 (2013) 348–356.

[15] O. Mahian et al., A review of the applications of nanofluids in solar energy, Int. J. Heat Mass Transfer 57 (2) (2013) 582–594.

[16] Y. Luo et al., Thermal energy storage enhancement of a binary molten salt via in-situ produced nanoparticles, Int. J. Heat Mass Transfer 104 (2017) 658–664.

[17] M. Sharifpur, S.A. Adio, J.P. Meyer, Experimental investigation and model development for effective viscosity of Al_2O_3–glycerol nanofluids by using dimensional analysis and GMDH-NN methods, Int. Commun. Heat Mass Transfer 68 (2015) 208–219.

[18] S.S. Harandi et al., An experimental study on thermal conductivity of F-MWCNTs–Fe_3O_4/EG hybrid nanofluid: effects of temperature and concentration, Int. Commun. Heat Mass Transfer 76 (2016) 171–177.

[19] Y. Yang et al., Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow, Int. J. Heat Mass Transfer 48 (6) (2005) 1107–1116.

[20] R. Ranjbarzadeh, A.H. Meghdadi, M. Hojaji, The analysis of experimental process of production, stabilizing and measurement of the thermal conductivity coefficient of water/graphene oxide as a cooling nanofluid in machining, J. Modern Process. Manuf. Prod. 5 (2) (2016) 43–53.

[21] M. Mehrali et al., An ecofriendly graphene-based nanofluid for heat transfer applications, J. Clean. Prod. 137 (2016) 555–566.

[22] E. Ebrahimnia-Bajestan et al., Experimental and numerical investigation of nanofluids heat transfer characteristics for application in solar heat exchangers, Int. J. Heat Mass Transfer 92 (2016) 1041–1052.

[23] P.D. Prasad, A. Gupta, Experimental investigation on enhancement of heat transfer using Al_2O_3/water nanofluid in a u-tube with twisted tape inserts, Int. Commun. Heat Mass Transfer 75 (2016) 154–161.

[24] W. Yu et al., Significant thermal conductivity enhancement for nanofluids containing graphene nanosheets, Phys. Lett. A 375 (10) (2011) 1323–1328.

[25] R. Kamatchi, S. Venkatachalapathy, B.A. Srinivas, Synthesis, stability, transport properties, and surface wettability of reduced graphene oxide/water nanofluids, Int. J. Therm. Sci. 97 (2015) 17–25.

[26] Z. Hajjar, A. Morad Rashidi, A. Ghozatloo, Enhanced thermal conductivities of graphene oxide nanofluids, Int. Commun. Heat Mass Transfer 57 (2014) 128–131.

[27] A. Amrollahi et al., Convection heat transfer of functionalized MWNT in aqueous fluids in laminar and turbulent flow at the entrance region, Int. Commun. Heat Mass Transfer 37 (6) (2010) 717–723.

[28] E. Sadeghinezhad et al., Experimental investigation of convective heat transfer using graphene nanoplatelet based nanofluids under turbulent flow conditions, Ind. Eng. Chem. Res. 53 (31) (2014) 12455–12465.

[29] M. Mehrali et al., Heat transfer and entropy generation for laminar forced convection flow of graphene nanoplatelets nanofluids in a horizontal tube, Int. Commun. Heat Mass Transfer 66 (2015) 23–31.

[30] E. Sadeghinezhad et al., An experimental and numerical investigation of heat transfer enhancement for graphene nanoplatelets nanofluids in turbulent flow conditions, Int. J. Heat Mass Transfer 81 (2015) 41–51.

[31] S.Z. Heris, M.N. Esfahany, S.G. Etemad, Experimental investigation of convective heat transfer of Al_2O_3/water nanofluid in circular tube, Int. J. Heat Fluid Flow 28 (2) (2007) 203–210.

[32] F. Hekmatipour, M. Akhavan-Behabadi, B. Sajadi, Combined free and forced convection heat transfer of the copper oxide-heat transfer oil (CuO-HTO) nanofluid inside horizontal tubes under constant wall temperature, Appl. Therm. Eng. 100 (2016) 621–627.

[33] M. Rakhsha et al., Experimental and numerical investigations of turbulent forced convection flow of nano-fluid in helical coiled tubes at constant surface temperature, Powder Technol. 283 (2015) 178–189.

[34] P. Naphon, Experimental investigation the nanofluids heat transfer characteristics in horizontal spirally coiled tubes, Int. J. Heat Mass Transfer 93 (2016) 293–300.

[35] X.-Q. Wang, A.S. Mujumdar, A review on nanofluids-part II: Experiments and applications, Braz. J. Chem. Eng. 25 (4) (2008) 631–648.

[36] R. Ranjbarzadeh et al., An experimental study on heat transfer and pressure drop of water/graphene oxide nanofluid in a copper tube under air cross-flow: applicable as a heat exchanger, Appl. Therm. Eng. 125 (2017) 69–79.

[37] E. Haghighi et al., Shelf stability of nanofluids and its effect on thermal conductivity and viscosity, Meas. Sci. Technol. 24 (10) (2013) 105301.

[38] V. Bianco, O. Manca, S. Nardini, Performance analysis of turbulent convection heat transfer of Al_2O_3 water-nanofluid in circular tubes at constant wall temperature, Energy 77 (2014) 403–413.

[39] E. Sadeghinezhad et al., A comprehensive review on graphene nanofluids: recent research, development and applications, Energy Convers. Manage. 111 (2016) 466–487.

[40] B.C. Pak, Y.I. Cho, Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles, Exp. Heat Transf. Int. J. 11 (2) (1998) 151–170.

[41] A. Ijam et al., Stability, thermo-physical properties, and electrical conductivity of graphene oxide-deionized water/ethylene glycol based nanofluid, Int. J. Heat Mass Transfer 87 (2015) 92–103.

[42] T.L. Bergman et al., Fundamentals of Heat and Mass Transfer, John Wiley & Sons, 2011.

[43] R.J. Moffat, Describing the uncertainties in experimental results, Exp. Therm. Fluid Sci. 1 (1) (1988) 3–17.

[44] S.E.B. Maïga et al., Heat transfer behaviours of nanofluids in a uniformly heated tube, Superlatt. Microstruct. 35 (3) (2004) 543–557.

[45] S. Fotukian, M.N. Esfahany, Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube, Int. Commun. Heat Mass Transfer 37 (2) (2010) 214–219.

[46] M.H. Esfe et al., Heat transfer characteristics and pressure drop of COOH-functionalized DWCNTs/water nanofluid in turbulent flow at low concentrations, Int. J. Heat Mass Transfer 73 (2014) 186–194.

[47] M.H. Esfe et al., Thermophysical properties, heat transfer and pressure drop of COOH-functionalized multi walled carbon nanotubes/water nanofluids, Int. Commun. Heat Mass Transfer 58 (2014) 176–183.

[48] S. Fotukian, M.N. Esfahany, Experimental investigation of turbulent convective heat transfer of dilute γ-Al_2O_3/water nanofluid inside a circular tube, Int. J. Heat Fluid Flow 31 (4) (2010) 606–612.

[49] A. Ghozatloo, A. Rashidi, M. Shariaty-Niassar, Convective heat transfer enhancement of graphene nanofluids in shell and tube heat exchanger, Exp. Thermal Fluid Sci. 53 (2014) 136–141.

[50] H. Yarmand et al., Experimental investigation of thermo-physical properties, convective heat transfer and pressure drop of functionalized graphene nanoplatelets aqueous nanofluid in a square heated pipe, Energy Convers. Manage. 114 (2016) 38–49.