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Experimental investigation of laminar forced convective heat transfer of Graphene–water nanofluid inside a circular tube

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In this paper, convective heat transfer coefficient of Graphene–water nanofluid in a laminar flow through a circular pipe with uniform wall heat flux is investigated experimentally. To achieve this aim, the nanofluid is synthesized chemically in various concentrations, and a testbed is constructed. The effective thermal conductivity and viscosity of the Graphene–water nanofluids are measured via hot wire method and an Ubbelohde viscometer, respectively. Results show that addition of low amounts (up to 0.02% volume fraction) of Graphene nanoparticles to water considerably increases the thermal conductivity and the convective heat transfer coefficient of the working fluid. Maximum enhancements are observed at 0.02% concentration. These enhancements are 10.3% for thermal conductivity and 14.2% for heat transfer coefficient at Re = 1850. Moreover, the stability of the prepared nanofluids is examined by using the UV–vis spectroscopy and is proved to be acceptably high. Finally, the results of the taken AFM images implied no agglomeration of nanoparticles.

1. Introduction

Considering the fast progress of science and the increasing demand of industries for high heat transfer rates, lots of efforts have been made in order to find novel ways of heat transfer enhancement. Although many methods like increasing the heat transfer surface, changing the geometry, and applying electric or magnetic fields have been used successfully, they can hardly meet today's requirements of heat flux dissipation and heat transfer.

To date, lots of researchers have adopted new ways of enhancing the fluid performance by mixing it with solid particles of various sizes, among which nanoparticles (with at least one dimension normally less than 100 nm) have been the center of concentration because of their special merits compared to milli-sized and micro-sized particles. Stability of particles and lack of clogging of flow passages are of these merits. Choi [1] and Masuda et al. [2] are probably the first researchers who suspended nanoparticles in basefluids and found considerable enhancements in heat transfer performance in comparison to the basefluids.

Up to now, several researchers have focused on measuring the effective thermal conductivity of nanofluids [3–5]. A comprehensive review of experimental investigations on the thermal conductivity of nanofluids by various researchers has been gathered by Wang and Mujumder [6].

In addition to thermal conductivity, various studies have been conducted on the enhancement of convective heat transfer in laminar and turbulent flows with different nanoparticle and various concentrations [7–10].

Considering the main idea of addition of nanoparticles to conventional fluids, i.e. enhancing the heat transfer performance of the working fluid by making improvements in thermal conductivity, massive research has been dedicated to introducing new materials with super thermal conductivity properties. Among all of the propositions, higher thermal conductivity and lower density of carbon materials compared to metals and metal oxides have made them the most attractive substances. In this regard, many investigations have been carried out to study the properties of various structural forms of carbon nano materials such as carbon nanotubes [11,12], graphite nanoparticles [13], and diamond nanoparticles [14]. Graphene, a two dimensional material with one

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Nomenclature

c_p	specific heat (J/kg K)
d	diameter of the tube (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	tube length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number, $\mathrm{Nu}(x) = h(x).d_i/k$
P	tube inner perimeter (m), $P = \pi.d_i$
Pr	Prandtl number, $\mathrm{Pr} = \mu.c_P/k$
q''	heat flux (W/m^2)
Q	volumetric flow rate
Re	Reynolds number, $\mathrm{Re} = \rho.V.d_i/\mu$
T	temperature (°C)
V	average velocity (m/s)
x	distance from the tube inlet (m)
x_*	dimensionless length, $x_* = [(x/d_i)/(\mathrm{Re.Pr})]$

Greek symbols

Δ	difference operator
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

bf	Basefluid
i	inner surface of the tube wall
in	Inlet
m	Bulk
nf	Nanofluid
o	outer surface of the tube wall
w	Wall

carbon atom thickness, first discovered by Novoselov et al. [15], can be considered as the best carbonic structural form for use in nanofluids due to its unique thermal properties. According to the study of Balandin et al. [16], the in-plane thermal conductivity of Graphene can reach up to 5200 W/mK which shows its superiority to carbon nanotubes with axial thermal conductivity of about 3000 W/mK [17]. Yu et al. [18] studied the thermal conductivity of Graphene/ethylene glycol nanofluids and observed up to 86% enhancement in thermal conductivity at 5% volume fraction of Graphene nanosheets. Gupta et al. [19] measured thermal conductivity of dispersions of Graphene nanosheets in water via transient hot wire method and observed strong temperature dependency of the results. They proposed a combination of percolation, Brownian motion, and micro convection effects to explain the observed thermal conductivity behaviors of Graphene–water nanofluid. Baby and Ramaprabhu [20] performed an experimental study on the enhanced convective heat transfer of Graphene–water nanofluids. For 0.05% concentration, they reported 16% and 75% enhancements in thermal conductivity at 25 °C and 50 °C respectively. Moreover, their results showed more enhancements in the Nusselt number compared to the thermal conductivity. Turbulent convective heat transfer of Graphene–water nanofluid with various concentrations inside a uniformly heated circular tube was studied by Akhavan-Zanjani et al. [21]. They found that Nusselt number generally decrease with the addition of nanoparticles and the maximum enhancement in heat transfer coefficient was 6.04% which occurred at a volume fraction of 0.02% at Re = 10,850.

As there is rather little report on a Graphene nanofluid and its thermal properties, this article is going to perform a comprehensive study on these nanofluid thermo-physical properties and laminar convective heat transfer inside a tube. In the present work, the Graphene–water nanofluid is studied and introduced as a useful working fluid for use in industrial heat transfer applications. For this purpose, Graphene nanosheets have been synthesized chemically, thermal conductivity, viscosity, and heat transfer coefficient of the Graphene–water nanofluid have been experimentally measured, and the effects of particles concentration and Reynolds number on these parameters have been reported and analyzed.

2. Material

Various methods have been proposed for preparation of Graphene, such as micromechanical cleavage [15], solvothermal synthesis [22], and chemical vapor deposition [23]. Among these methods, chemical ones are more preferable due to their potential for bulk production [24]. Accordingly, in this study, Graphene–water nanofluid was made according to the chemical method introduced by Gudarzi and Sharif [25]. For producing the Graphene–water nanofluid, Graphene oxide (GO) was prepared and reduced to make the Graphene nanoparticles. For this purpose, Graphite powder was purchased from Merck chemicals. Also, PVA was obtained from DC chemical, Korea, and used as a dispersant to prevent agglomeration of nanoparticles. All other agents were purchased from Merck chemicals. Distilled water was used as the basefluid. Graphite oxide was synthesized by Hummer's method [26]. After the black color mixture of Graphene nanoparticles produced, specific amounts of water were added to obtain the desired volume fractions.

Fig. 1(a) illustrates an AFM (Atomic Force Microscopy) image of Graphene Sheets which were coated on the spinning freshly cleaved mica. Distributions of thickness of Graphene sheets plus their attached PVA layers are obtained along two straight lines and shown in Fig. 1(b). The results show that the thickness of the composite sheets is within the range of about 1.4 nm–2.3 nm and their lateral size is from about 270 nm up to 1.5 μm. It can be understood from the work of Gudarzi and Sharif [25] that the minimum thickness of the PVA layers is 0.5 nm (1 nm for both sides of each nanosheet) which indicates that the maximum thickness of the Graphene sheets, in this study, is in the range of 0.4 nm–1.3 nm. Moreover, the typical thickness of a Graphene sheet is about 0.34 nm theoretically [17]. Considering this fact and the previously obtained range for the thickness of produced Graphene nanosheets, it can be concluded that most of the produced nanosheets are monolayer or bilayer. Gudarzi and Sharif [25] proved that the stability of these water-based Graphene nanofluids is physically stable.

The effective viscosity of the nanofluid was measured by using an Ubbelohde viscometer which works based on calculating the time required for a particular quantity of fluid to pass through a capillary bore. The maximum relative error of measuring the viscosity ratio was approximately 1%. The measured values of viscosity for various concentrations are shown in Fig. 2 for 25 °C and 35 °C temperatures. As is seen from the figure, increase in concentration and decrease in temperature lead to increase in the viscosity of the nanofluid. For comparing the obtained results with those predicted by various models, such as Einstein [27], Brinkman [28], and Batchelor [29], the measured values of viscosity ratio for 25 °C at different volume fractions are Tabulate in Table 1. Beside those predicted by the models. It can be seen from the figure that the measured values of viscosity ratio show nonlinear behavior with respect to concentration. This nonlinear behavior is an indication of