International Journal of Heat and Mass Transfer 119 (2018) 408–417

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermophysical performance of graphene based aqueous nanofluids

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ARTICLE INFO

Article history:
Received 21 December 2016
Received in revised form 12 August 2017
Accepted 6 November 2017

Keywords:
Graphene nanofluids
Non-Newtonian fluids
Thermophysical properties
Friction factor
Nusselt number
Pseudoplastic behavior
Power Law fluids

ABSTRACT

Study of thermophysical properties and forced convective heat transfer performance and flow characteristics for single layer graphene (GNP) based nanofluids was undertaken. Experimental results reveal that GNP mass fraction increases both the effective thermal conductivity and viscosity of the nanofluid. Furthermore, the graphene nanofluid suspensions exhibit a shear thinning behavior, which follows the Power Law viscosity model with a flow behavior index of about 0.938, suggesting particle–particle interactions. Experimental results show that inclusion of GNP in the host fluid increases pressure drop by 112–161% at the same flow rates. A new friction factor correlation is proposed for 1 wt% GNP nanofluids flowing through a circular pipe as non-Newtonian fluid. Furthermore, the Nusselt number (Nu) of GNP nanofluids decreases with axial distance at a much slower rate than that of the base fluid (water) due to viscous effect and particle interactions within the nanofluids. In addition, Nu values of GNP nanofluids are higher than for water under laminar flow conditions. Based on the classic Nu model for non-Newtonian flow in a uniformly heated circular pipe under laminar flow conditions, a new Nu correlation is proposed for 1 wt% GNP nanofluids, which fits the experimental data well.

1. Introduction

As thermal loads keep increasing in many energy transport related engineering applications, greater amounts of heat transfer fluids as well as larger heat transfer systems are needed to meet the continuously growing cooling demands. Therefore, in order to meet increasing thermal demands, researchers have to use either enhanced heat transfer surfaces or better heat transfer fluids, to improve the overall efficiency and lifetime of energy transport systems.

One way to achieve improved heat transfer fluids is to mix base fluids with nano-sized particles. Choi and Eastman [1] introduced the concept of nanofluids for heat transfer applications, by proving that adding nanoparticles could improve the thermophysical properties of the host heat transfer fluid including thermal conductivity [1–6], and eventually heat transfer performance [7–11]. Nanofluids consisting of graphene nanoparticles (GNP) is one of the most promising heat transfer fluids due to the relatively high thermal conductivity of GNP (5000 W/m-K). Accordingly, many studies have investigated thermophysical properties and convective heat transfer performance of GNP nanofluids, as reported briefly below.

1.1. Thermal conductivity of graphene nanofluids

Yu et al. [12] found that ethylene glycol with 5 vol% of GNP exhibits up to 86% thermal conductivity enhancement. Sadeghinezhad et al. [14] reported thermal conductivity data for GNP nanofluids showing an enhancement of thermal conductivity in the range of 8–25%. Kole and Dey [15] also claimed that the thermal conductivity of nanofluids depends positively on both temperature and mass fractions of nanoparticles. Gupta et al. [16] found considerable thermal conductivity enhancements for nanofluids with low particle concentrations. They claimed that the increase of thermal conductivity strongly depends on temperature.

1.2. Viscosity of graphene nanofluids

Sadeghinezhad et al. [17] found out that the viscosity of GNP nanofluids depends both on fluid temperature and the mass fraction of nanoparticles, in which the viscosity increase is in the range from 9% to 38%. Mehrali et al. [22] studied the viscosity of similar GNP nanofluids [17], in which they found that GNP nanofluid viscosity decreases with temperature and increases with GNP concentration. In the study, the viscosity of 0.1 wt% GNP nanofluids was 44% greater than the base fluid. The GNP nanofluid also exhibited shear thinning behavior. The study by Kole and Dey [15] shows a

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.019
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Nomenclature

c_p	specific heat, kJ/kg-°C
D	tube diameter, m
DAQ	data acquisition
DC	direct current
DI	distilled
DPT	differential pressure transducer
EG	ethylene glycol
f	friction factor
FM	flow meter
GNP	graphene
Gz	Graetz number
h	heat transfer coefficient, kW/m^2-°C
HX	heat exchanger
K	flow consistency index, Pa s^n
k	thermal conductivity of the fluid, W/m-°C
L	tube length, m
$\dot{m}$	mass flow rate, kg/s
MF	mass fraction of GNP nanofluid
n	flow behavior index
NIST	National Institute of Standards and Technology
Nu	Nusselt number
p	perimeter of the tube, m
Pr	Prandtl number
ΔP	pressure difference between inlet and outlet of the tube, kPa
q''	heat flux, kW/m^2
Re	Reynolds number
RPM	revolutions per minute
R^2	coefficient of determination
T	temperature, °C
TS	test station
u	fluid velocity, m/s
$vol.\%$	volume fraction of nanofluids
$wt\%$	weight percentage of the GNP nanofluid
x	axial position along the tube, m
Greek symbols	
ρ	fluid density, kg/m^3
μ	dynamic viscosity, mPa-s
γ	shear rate, 1/s
τ	shear stress, Pa
Subscripts	
b	bulk
H	hydraulic
i	tube inlet
L	local values
o	tube outlet
s	surface

100% viscosity increase for GNP nanofluids with respect to the base liquid, in which the nanofluids exhibited non-Newtonian behavior. Moghaddam et al. [19] showed that the viscosity of GNP nanofluids increases with increasing nanoparticle mass fractions and decreases with temperature as seen in other studies. A shear thinning behavior of GNP nanofluids was also observed. Table 1. summarizes key observations about GNP nanofluids in terms of thermal-physical properties from different studies.

1.3. Pressure drop of graphene nanofluids

Sadeghinezhad et al. [17] found that pressure drop of GNP nanofluids increases linearly with nanoparticle concentration. In a subsequent study [14], it was found that pumping power of the system increased slightly even though pressure drop increased up to 14.6%. Akhavan-Zanjani et al.'s [20] work shows that pressure drop and friction factor of GNP nanofluids do not change with nanoparticle volume fraction considerably, but pressure drop increases and friction factor decreases with Reynolds number. Mehrali et al. [22] experimental results indicate that pressure drop of GNP nanofluids increases up to 14.4% when compared to the base fluid.

1.4. Convective heat transfer of graphene nanofluids

Baby and Ramaprabhu [13] observed Nusselt number enhancement for GNP nanofluids when compared to DI water even though the thermal conductivity enhancement associated with exfoliated GNP was relatively modest. Sadeghinezhad et al. [17] conducted both experimental and numerical studies and revealed that the Nusselt number of GNP nanofluids increased by approximately 3–83% as the flow rate and heat flux increased. Ghozatloo et al. [23] reported that the convective heat transfer coefficient of 0.1 wt% GNP nanofluids at 38 °C was 35.6% greater than for pure water. It was suggested that the effect of nanoparticle mass fraction is a more dominant factor than fluid temperature on heat transfer performance of nanofluids. Akhavan-Zanjani et al. [20] found that the convective heat transfer coefficient of GNP nanofluids was enhanced by just 6.0% while the maximum increase of thermal conductivity and viscosity of GNP nanofluids was 10.3% and 5.0%, respectively. Prasher et al. [24] experimentally and theoretically evaluated the effect of viscosity and thermal conductivity enhancement ratio on heat transfer performance of nanofluids. It was concluded that viscosity increments should not increase by more than 4-fold when compared to thermal conductivity enhancements in order to maintain the nanofluids' convective heat transfer enhancement greater than unity.

Tables 2 and 3 summarize the key observations about pressure drop and convective heat transfer of GNP nanofluids in the literature, respectively.

2. Description of graphene nanofluids and experimental apparatuses

2.1. Description of graphene nanofluids

The GNP nanofluids used in this study were purchased from US Research Nanomaterials, Inc. According to the manufacturer and based on the fluid specifications, a special dispersant was used in the solvent to ensure GNP stability over an extended period of time. Furthermore, a high capacity ultrasonic machine was used to form very uniform and very stable graphene-based nanofluids. The detailed specifications of GNP nanofluids used in the study are shown in Table 4, as provided by manufacturer. In addition, TEM and SEM images of single layer GNP used in this study can be seen in Figs.1 and 2.

2.2. Description of viscosity apparatus

In the study, the viscosity of the corresponding GNP nanofluids was characterized by using a coaxial rotating drum viscometer