International Journal of Heat and Mass Transfer 81 (2015) 41–51

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

An experimental and numerical investigation of heat transfer enhancement for graphene nanoplatelets nanofluids in turbulent flow conditions

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ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form 1 October 2014
Accepted 2 October 2014
Available online 23 October 2014

Keywords:
Graphene nanoplatelets nanofluid
Convective heat transfer
Experimental
Numerical simulation
Turbulent flow
Thermo-physical properties

ABSTRACT

In this paper, both experimental and numerical studies have been performed on the turbulent heat transfer of the graphene nanoplatelets nanofluids in a horizontal stainless steel tube that was subjected to a uniform heat flux at its outer surface. An experimental investigation was done to evaluate the heat transfer characteristics and the pressure drop of a graphene nanoplatelet (GNP) nanofluid and in numerical study, the finite volume method with standard k–ε turbulence model is employed to solve the continuity, momentum, energy and turbulence equations in three dimensional domains. The thermal conductivity and viscosity of the GNP nanofluids at concentrations of 0.025, 0.05, 0.075, and 0.1 wt% were measured prior to the heat transfer experiments. The heat transfer and the pressure drop within the flowing base fluid (distilled water) were measured and compared with the corresponding data from the correlations and numerical study. The data were satisfied within a 5% error and 2% error for the numerical work. The effects of the nanoparticle concentration and the heat flux on the enhancement of the heat transfer turbulent flow condition are presented. The Nusselt number (Nu) of the GNP nanofluid was higher than the base fluid by approximately 3–83% and increased as the flow rate and the heat flux increased. However, the increase in the pressure drop ranged from 0.4% to 14.6%. Finally, the results reveals that the GNP nanofluids could function as a good and alternative conventional working fluid in heat transfer applications.

1. Introduction

Energy transport is an integral part of a wide range of fields, including oil and gas, nuclear energy, and electrical energy. Water, oil, and ethylene glycol (EG) are used as heat transfer fluids. However, the development of heat transfer fluids with an improved thermal conductivity has become increasingly critical to the performance of energy systems [1,2]. Choi and Eastman [3] have introduced the term nanofluids, which refer to fluids that contain dispersed nano-sized particles that have a higher thermal conductivity [4]. Nanofluids improve thermo-physical properties [5], such as the thermal diffusivity and the thermal conductivity, provide excellent stability and convective heat transfer coefficients, and only slightly increase the pressure drop and required pumping power [6]. Many studies have been conducted to enhance the thermal properties of heat transfer fluids by adding highly thermally conductive nanoparticles [7]. Recently, a significant number of studies have been performed on carbon-based nanostructures [8], including carbon fiber [9], carbon black [10], carbon nanotubes (CNTs) [11], graphite [12], graphene oxide (GO) [13], graphene [14], and graphite flakes [15].

An experimental investigation of the convective heat transfer coefficient for nanofluids flowing through different types of tubes has been conducted in several studies [16], and these have considered different types of nanoparticles, including oxides, nitrides, metals, diamond, and carbon-based nanoparticles [17,18]. Early

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.006
0017-9310/

Nomenclature

C_p	specific heat capacity, J/kg K
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k, σ_ε	model constants
D	tube diameter, m
DW	distilled water
f	friction factor
G_b	generation of turbulence kinetic energy
h	convective heat transfer coefficient
I	electrical current, A
k	thermal conductivity, W/m K
L	tube length, m
Nu	Nusselt number
P	heater power, W
Pr	Prandtl number
q''	heat flux, W/m^2
Re	Reynolds number
T	temperature, K
V	volts, V
U	mean velocity, m/s
w	water
wt%	weight percentage
X, Y, Z	Cartesian coordinates

Greek

μ	dynamic viscosity, Pa s
μ_t	turbulent viscosity
ε	turbulent dissipation
ρ	density, kg/m^3
η	thermal performance factor

Subscripts

avg	average
b	bulk
bf	base fluid
i	inner
in	inlet
m	mean
nf	nanofluid
np	nanoparticle
o	outer
out	outlet
w	wall

experiments with TiO_2, Al_2O_3, and SiO_2 nanofluids were undertaken by different researchers to determine the effect of the nanofluid concentration on the thermo-physical properties and the heat transfer coefficient [19,20]. They observed an increase in the convective heat transfer coefficients at various concentrations of the nanofluid under laminar and turbulent flow conditions from 20% to 350% [20,21]. They concluded that the influence of the nanofluid concentration on the heat transfer coefficient is significant in the turbulent region versus the laminar region [22,23]. However, only limited research has been performed on convective heat transfer when using carbon-based nanofluids as the heat transfer liquid compared with many results for the thermo-physical properties of nanofluids [22].

Numerical modeling of convective heat transfer of nanofluids can be conducted using single-phase or multi-phase approaches. Most of the studies in this area have been made using single-phase model [24–26]. The numerical and experimental works on the effective thermal conductivity and convective heat transfer are needed to demonstrate the full potential of nanofluids [27] and to understand the fundamentals of heat transfer for developing new nanofluid. Although there are recent developments in the theoretical and experimental results to understanding of the particle movements mechanisms, heat transfer and fluid flow behavior of nanofluids [27]. Many research works are available on the numerical study of convective heat transfer of nanofluids, there is no complete research on various effective parameters in this area, including based fluid, nanoparticle shape, and type of nanoparticles. However, improvement in heat transfer performance due to the nanofluids is accompanied by a number of undesired effects, including pressure drop and pumping power. Hence, it requires to obtain the proper nanofluid for optimum operation of heat transfer applications [28].

The aqueous suspensions of stable homogeneous GNP nanofluids were prepared by high-power ultrasonication. The stability and the thermo-physical properties of the GNPs have been reported previously by Mehrali et al. [1]. The main scope of the present study is to identify the uncertainties in experimental and theoretical formulations due to the effects of aqueous GNP (specific surface areas of 500 m^2/g) nanofluid on surface temperature and Nusselt number. The effects on the convective heat transfer that is derived from the different heat fluxes (8231, 10,351, 12,320 W/m^2) of the GNP nanofluid at different concentrations (0.25, 0.05, 0.075, and 0.1 wt%) under different Reynolds number varied from 4583 to 18,187.

2. Description of the experiment

2.1. Experimental system

The experimental setup for this work is shown in Fig. 1. It consists of a flow loop (with a bypass), a heating unit, a cooling part, measuring instruments, and a control unit. The flow loop includes a pump, a magnetic flow meter, a reservoir tank, a differential pressure transmitter, and a test section. The nanofluids were pumped from a 14-L capacity stainless steel jacketed tank by a Cole-Parmer magnetic drive pump at a flow rate of 0–10 l/m, and the pump flow was controlled by a Hoffman Muller inverter. The flow rate and the pressure loss were measured using a magnetic flow meter and a differential pressure transmitter, respectively. A straight stainless steel tube with a length of 1400 mm, a 12 ± 0.2-mm outer diameter, and a 10-mm inner diameter was used as the test section. The test section was heated using an ultra-high-temperature heating tape (Omega, USA) at a maximum power of 900 W, which was linked to a Variac transformer and a watt/amp meter. Five type K thermocouples (Omega, Singapore) were fixed using a high-temperature epoxy glue at equal axial distances on the outer surface of the test tube (Fig. 2).

To measure the cold and hot nanofluid temperatures, two RTD (PT-100) sensors (Omega, Singapore) were inserted to measure the bulk temperature at the inlet and outlet of the test section. All thermocouples and RTDs were calibrated against an Ametek temperature calibrator (AMETEK Test & Calibration Instruments, Denmark). The thermocouples were connected to the Graphtec (midi logger gl220), and the RTDs were connected to the Scada system for the continuous monitoring and recording of the temperature data by a personal computer. To minimize the heat loss to the surroundings, a thick glass wool wrapping was used. This insulation's heat loss temperature was measured by three type K thermocouples that were located on the outer surface of the insulation.