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Original Research Paper

Experimental investigation of thermophysical properties, entropy generation and convective heat transfer for a nitrogen-doped graphene nanofluid in a laminar flow regime

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ABSTRACT

Nitrogen-doped graphene (NDG) nanofluids are prepared using a two-step method in an aqueous solution of 0.025 wt% Triton X-100 as a surfactant with various nanosheets at several concentrations (0.01, 0.02, 0.04, 0.06 wt%). The results are reported of experiments on the thermal conductivity, viscosity and convective heat transfer behavior of NDG nanofluids undergoing laminar flowing in a circular tube. The results indicate that, compared to the base liquid, the thermal conductivity is enhanced for NDG nanofluids by between 22.15% and 36.78%, and the heat transfer coefficient of the NDG nanofluids is increased by 7–50%. The measurements also show that the pressure drop of the nanofluids increased by between 0.08% and 14.4%. In addition, the overall performance of the tested nanofluids are assessed based on the performance index and optimum work conditions, demonstrating that the nanofluids can be advantageous in practical applications.

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1. Introduction

Improving heat transfer performance is important to many disciplines. With the development of heat engines, heat pumps and similar devices, the requirement for better heat transfer has become increasingly important [1,2], spurring efforts to enhance heat exchanger designs and heat transfer fluids [2]. High-performance heat exchange fluids are widely needed for industrial technologies [3]. The preference for more compact heat transfer devices is growing in industry today [4] while, at the same time, heat transfer requirements of these devices are becoming more demanding. Increasing the heat transfer surface area of a device may not be adequate because practical constraints, like limits on manufacturing smaller channels or components, can be problematic [5,6].

As a consequence, various studies have been undertaken to increase the cooling and/or heating performance of working fluids [5,7,8]. This often involves the utilization of nanoparticles or other nanostructures, which not only improve the stability and applicability of liquid suspensions, but also increases the thermal conductivity, specific surface area and diffusion mobility of Brownian motion of the particles [9,10]. Nanoparticles are generally considered to be a recent discovery, however their history is long. Recently, newly developed nanometer sized particles have been used as a suspension in conventional heat transfer fluids [2,11]. Recent studies demonstrate that carbon based materials have a very high thermal conductivity compared to other types of nanoparticles, so it is anticipated that carbon based nanofluids will exhibit higher thermal conductivities than more conventional fluids [12,13]. A significant number of studies have been conducted with carbon based nanoparticles, in an attempt to exploit their unique thermal, mechanical, electrical, and other relevant characteristics [14–16]. The following mechanisms are believed to be responsible for the enhancement of the heat transfer coefficient in nanofluids:

1. Non-uniform distribution of thermal conductivity and viscosity field due to influence of particle migration and Brownian motion.

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Nomenclature

c_p	specific heat capacity at constant pressure (J/kg K)
d	tube diameter (m)
$\dot{E}_{gen}$	entropy generation rate (W/K)
f	friction factor
h	convective heat transfer coefficient (W/m^2 K)
I	electrical current (A)
k	thermal conductivity (W/m K)
L	tube length (m)
Nu	Nusselt number
P	pressure (Pa)
q''	heat flux (W/m^2)
Re	Reynolds number
T	temperature (K)
V	voltage
v	mean velocity (m/s)
x	axial distance (m)
η	performance index
μ	viscosity (Pa s)
ρ	density (kg/m^3)

Acronyms

DW	distilled water
FESEM	field emission scanning electron microscopy
NDG	nitrogen-doped graphene
SAED	selected area (electron) diffraction
TEM	transmission electron microscopy
UV–vis	UV–vis spectrophotograph
wt%	weight percentage

Subscripts

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

2. Reduction in thermal boundary layer thickness.
3. Rise in value of thermal conductivity and Reynolds number of nanofluids.
4. Enhanced heat transfer performance of nanofluids due to the reduction in boundary layer thickness by mixing effects of particles near the wall.

Several experimental investigations have been conducted on the convective heat transfer coefficient of various types of nanofluids flowing through tubes, including oxides, nitrides, metals, diamond, and carbon based nanoparticles [2,17]. The heat transfer coefficient of the nanofluid also depends on a number of factors such as the thermal conductivity and specific heat capacity of the base fluid and nanoparticles, the flow pattern, the viscosity of the nanofluid, the concentration of the suspended nanoparticles, the dimensions and shape of the particles, and the flow structure [18,19]. However, few investigations have been performed on the convective heat transfer characteristics of carbon based nanofluids in relation to their thermophysical properties [20,21].

Xuan and Li [22] studied the heat transfer of nanofluids under single-phase, turbulent flow in a horizontal tubes, and found that the Nusselt number of nanofluids increases by more than 39% with the volume fraction of nanoparticles and Reynolds number (Re). Other researchers have investigated the entry region under laminar flow conditions using nanofluids containing γ-Al_2O_3 nanoparticles of various concentrations [23]. Wen and Ding [23] demonstrated that the enhancement of the local heat transfer coefficient at axial positions in the entry region is between 41% and 47% for values of Re between 1050 and 1600. They also found that the enhancement increases with Reynolds number as well as nanoparticle concentration. Yang et al. [24] investigated the convective heat transfer coefficient of nanofluids for laminar flow over a horizontal tube, and found that nanofluids with a 2.5 wt% concentration exhibited an increase in convective heat transfer coefficient of 22% and that nanofluids generally exhibited an increase in thermal conductivity of about 50%. Ding et al. [25] measured the convective heat transfer coefficient of multi-walled carbon nanotubes in aqueous solutions with a concentration of 0.1–1.0 vol% and 0.5 wt% of gum Arabic as a dispersant, and observed an enhancement in heat transfer of 350% when $Re = 800$. A summary of the experimental forced convection studies of heat exchangers under laminar flow for various nanofluids is given in Table 1.

The objective of this research is to improve understanding of the effect of nitrogen-doped graphene (NDG) nanofluids concentration on the convective heat transfer coefficient and the friction factor under laminar flow, through experimental investigations. Such research on the convective heat transfer of NDG nanofluids in heat transfer systems is required for several reasons: (a) the convective heat transfer of NDG nanofluids has not been previously investigated, and (b) NDG has a high thermal conductivity and can improve the heat transfer coefficient of the base fluid. The NDG synthesized by heat treatment of graphene in an ammonia solution is followed by the preparation of stable nanofluids with desired characteristics. The present study examines the characteristics of NDG nanosheets and the stability, thermal conductivity, and viscosity of NDG nanofluids at several concentrations (0.01, 0.02, 0.04 and 0.06 wt%) with Triton X-100 as a surfactant. The variation of the convective heat transfer coefficient is investigated under heat fluxes of 3.5 kW/m^2 and an inlet temperature of 30 °C at various concentrations of NDG nanofluid under several bulk velocities ranging from 0.05 to 0.4 m/s (for which the Reynolds number varies from 290 to 2300).

2. Material preparation and characterization

A simplified Hummers' method was used to synthesize graphene oxide (GO) [33] and the NDG was prepared by a hydrothermal process with GO as raw material in an ammonia solution. As shown in Fig. 1, a mixture of 50-mg of GO and 100 mL of H_2O was sonicated for 1 h and the pH of the solution was adjusted to 11 using ammonia. This homogenous solution was hydrothermally treated in a Teflon-lined autoclave at a temperature of 160 °C for 12 h. A black woolly precipitate was collected by centrifugation, followed by washing with deionized water. Finally, the obtained NDG samples were dried at 50 °C under a vacuum.

The field emission scanning electron microscopy (FESEM) image in Fig. 2(a) shows a uniform structure like a crumpled silk veil with

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