International Communications in Heat and Mass Transfer 66 (2015) 23–31

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

# Heat transfer and entropy generation for laminar forced convection flow of graphene nanoplatelets nanofluids in a horizontal tube☆

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ARTICLE INFO

Available online 16 May 2015

*Keywords:*
Graphene nanoplatelets
Nanofluid
Convective heat transfer
Laminar flow
Entropy generation

ABSTRACT

The results are reported of an investigation of the heat transfer characteristics and entropy generation for a graphene nanoplatelets (GNP) nanofluid with specific surface area of 750 $m^2/g$ under laminar forced convection conditions inside a circular stainless steel tube subjected to constant wall heat flux. The analysis considers constant velocity flow and a concentration range from 0.025 wt.% to 0.1 wt.%. The impact of the dispersed nanoparticles concentration on thermal properties, convective heat transfer coefficient, thermal performance factor and entropy generation is investigated. An enhancement in thermal conductivity for GNP of between 12% and 28% is observed relative to the case without nanoparticles. The convective heat transfer coefficient for the GNP nanofluid is found to be up to 15% higher than for the base fluid. The heat transfer rate and thermal performance for 0.1 wt.% of GNP nanofluid is found to increase by a factor of up to 1.15. For constant velocity flow, frictional entropy generation increases and thermal entropy generation decreases with increasing nanoparticle concentration. But, the total entropy generation tends to decrease when nanoparticles are added at constant velocity and to decrease when velocity rises. Finally, it is demonstrated that a GNP nanofluid with a concentration between 0.075 wt.% and 0.1 wt.% is more energy efficient than for other concentrations. It appears that GNP nanofluids can function as working fluids in heat transfer applications and provide good alternatives to conventional working fluids in the thermal fluid systems.



## 1. Introduction

Conventional heat transfer fluids have naturally low thermal conductivities, significantly limiting the heat exchange efficiency of heat exchangers in which they are used [1]. As material modifications, use of extended surfaces, process parameter alterations and redesigning heat exchange equipment have already been exploited extensively to increase heat transfer rates, many research activities have now focused on enhancing the heat transfer fluid. Improving the thermal transport properties of fluids by adding thermally conductive solid particles has become a prominent research avenue [2]. A nanofluid is a suspension of nanoparticles in a base fluid, and nanofluids are considered promising heat exchanger fluids for enhancing heat transfer due to their high thermal conductivities. Presently, discrepancies exist in the literature regarding nanofluid thermal conductivity data, and the heat transfer enhancement mechanisms are not yet fully understood [3]. The heat transfer enhancement provided by nanofluids has been attributed to many mechanisms, including the following: 1) particle agglomeration, 2) nanoparticle concentrations, 3) Brownian motion, 4) thermophoresis, 5) nanoparticle size, 6) particle shape/specific surface area, 7) liquid layering on the nanoparticle-liquid interface, 8) working temperature, and 9) reduction in thermal boundary layer thickness [4]. Most research has focused on how various parameters affect thermal properties, rather than on the heat transfer process. It is generally more beneficial to add nanoparticles, when the base working fluid of a system has low thermal conductivity. The selection of the base fluid is primarily dependent on the heat transfer application specifications. One concern with the use of nanoparticles is that, although their dimensions are several nanometers, larger particles can lead to damage and corrosion difficulties for equipment such as pipelines and flow channels due to their high momentum and energy [5].

The convective heat transfer coefficient has been investigated experimentally in a flow loop at various flow rates and various nanoparticle sizes, concentrations and types ($Al_2O_3$, $TiO_2$, MgO, Cu, CuO, SiC, Ag, CNT) [6]. A number of experimental investigations have been reported on nanofluid flow in a tube. Researchers have experimentally observed for laminar flow heat transfer enhancements of up to 106% through the

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.05.007
0735-1933/

## Nomenclature

| | |
|---|---|
| $c_p$ | specific heat capacity at constant pressure, J/kg K |
| d | tube diameter, m |
| DW | distilled water |
| $\dot{E}_{gen}$ | entropy generation rate, W/K |
| f | friction factor |
| h | convective heat transfer coefficient |
| I | electrical current, A |
| k | thermal conductivity, W/m·K |
| l | tube length, m |
| GNP | graphene nanoplatelets |
| $\dot{m}$ | mass flow rate, kg/s |
| Nu | Nusselt number |
| P | pressure, Pa |
| $q''$ | heat flux, W/m$^2$ |
| Re | Reynolds number |
| T | temperature, K |
| UV–vis | UV–vis spectrophotograph |
| V | voltage |
| v | mean velocity, m/s |
| x | axial distance |

*Greek symbols*

| | |
|---|---|
| μ | viscosity, Pa·s |
| ρ | density, kg/m$^3$ |
| $\eta$ | performance index |

*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 |

use of nanofluids [7,8]. Ding, et al. [9] found that the relative enhancement of local heat transfer coefficient reached 350% for nanofluids with 0.5 wt.% carbon nanotube (CNT). Other researchers have reported lower local heat transfer coefficient enhancements for CNT nanofluids at higher concentrations [10,11]. Additionally, some researchers have reported that the heat transfer for nanofluids follows classical correlations for single phase fluids [12].

The performance of a thermal system can be assessed in part by determining the heat transfer characteristic of heat transfer fluid and the entropy generation. It has been shown that augmentation of convective heat transfer flow does not ensure improvement of thermodynamic efficiency due to irreversibilities [13], which can be measured by total entropy generation of when using nanofluids. Entropy generation analysis has been used to determine the more efficient of numerous thermal systems, where the entropy generation is caused by irreversibilities associated with such processes as chemical reaction, mixing, friction, and heat transfer across finite temperature differences. Bejan [14] has determined the entropy generation for forced convection for various geometries including circular tubes, boundary layers over a flat plate, and cross flow over a single cylinder.

Recently, significant research has been conducted on the use of carbon based nanostructure materials (i.e. graphene) to prepare nanofluids [15–17]. Graphene is a single-atom-thick sheet of hexagonally arrayed sp$^2$-bonded carbon atoms and has received considerable attention since it was discovered by Novoselov, et al. [18]. Graphene has attracted attention due to its advantageous thermal, mechanical, electrical, optical and other relevant characteristics. Research on graphene has focused on its characteristics, often using various spectroscopic and microscopic experimental techniques [19,20]. Based on the literature, however, data are lacking on flows of water-based graphene nanoplatelets (GNP) nanofluids in horizontal tube heat exchangers under laminar flow conditions [21]. Additionally, investigations have not been reported on the entropy generation of GNP nanofluids under laminar convective heat transfer in circular tubes subjected to a constant wall heat flux. Thus, it is intention of this research to bridge this gap and improve understanding of heat transfer and entropy generation for GNP nanofluids for such conditions.

In this article, GNP nanoparticles with a specific surface area of 750 m$^2$/g are dispersed in water to prepare nanofluids with concentrations up to 0.1 wt.%. Then, thermophysical properties of the nanofluids, including thermal conductivity and viscosity, are measured, and flow and heat transfer characteristics of the nanofluids are evaluated, including heat transfer coefficient (h), pressure drop, entropy generation, and thermal performance factor. The variation of the convective heat transfer coefficient is investigated under a heat flux of 3500 W/m$^2$ and an inlet temperature of 30 °C at various concentrations of GNP nanofluid up to 0.1 wt.% for bulk velocities ranging from 0.05 to 0.4 m/s (for which the Reynolds number Re varies from 290 to 2300).

## 2. Experimental approach and methods

### 2.1. Materials and nanofluid preparation

GNP nanoparticles (Grade C, specific surface area of 750 m$^2$/g, from XG Sciences, Inc., Lansing, MI, USA) and distilled water are used for the preparation of nanofluids. GNP nanoparticle diameters of 2 μm and thickness 2 nm are used. Based on our previous work [16], the nanofluid samples are prepared by dispersing GNP nanoparticle in distilled water using a high-powered ultrasonication probe (Sonics Vibra Cell, Ningbo Kesheng Ultrasonic Equipment Co., Ltd., Ningbo, China) that has a 1200-W output power and a 20-kHz frequency power supply. The nanofluid concentrations examined are 0.025, 0.05, 0.075, and 0.1 wt.%.

### 2.2. Experimental set up and procedure for heat transfer coefficient measurements

The heat transfer coefficients of GNP nanofluids are measured in horizontal stainless steel tubes with constant heat flux on the outer wall surface. A schematic diagram of the experimental set up is shown in Fig. 1. It consists of a flow loop, a heating unit, a cooling unit, measuring instruments, and a jacketed tank. The flow loop includes a pump, a flow meter, a differential pressure transmitter, a nanofluid tank, bypass loop and a test section.

A straight stainless steel tube of 2000 mm length, 4.5 mm inner diameter, and 6.5 mm outer diameter is used as the test section. The aspect ratio of $L \approx 0.05ReD (L = 596 \text{ mm})$ at the entrance of the test section is used to ensure that the flow is hydrodynamically developed, and the 1404 mm of test section is heated directly by a DC power supply (N8738A, 3300 W, from Agilent Technologies). Five type K thermocouples (self-adhering thermocouple, SA1XL-K-72, of Omega, with ±0.1 °C accuracy) are fixed at the outer surface of the tube at distances from the entry of 830 mm (TS1), 1064 mm (TS2), 1298 mm (TS3), 1532 mm (TS4), and 1766 mm (TS5) to measure the tube wall temperature. To measure the inlet and outlet bulk fluid temperatures of the test section, two K-type thermocouples (Customized, from Omega, with ±0.1 °C