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Experimental investigation of the propylene glycol-treated graphene nanoplatelets for the enhancement of closed conduit turbulent convective heat transfer☆

K.H. Solangi [a,*], Ahmad Amiri [a], M.R. Luhur [b], Soheila Ali Akbari Ghavimi [c], Mohd Nashrul Mohd Zubir [a], S.N. Kazi [a,*], A. Badarudin [a]

[a] *Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[b] *Department of Mechanical Engineering, Faculty of Engineering, Quaid-e-Awam University of Engineering Science and Technology Nawabshah, Sindh, Pakistan*
[c] *Department of Chemical Engineering, Faculty of Engineering, University of Missouri-, Columbia, United States*

A R T I C L E I N F O

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A B S T R A C T

This research investigated the heat transfer characteristics of propylene glycol-treated graphene nanoplatelet-based water (PGGNP-Water) nanofluid. To reach a stable collide in liquid media, miscible PG was decorated. The PGGNP-Water with specific surface area of 750 m^2/g used under closed conduit turbulent convective heat transfer inside a circular copper tube was subjected to constant wall heat fluxes 23,870 W/m^2 and 18,565 W/m^2. The experiments were conducted for a Reynolds number range of 3900–11,700. The impact of the dispersed nanoparticles concentration on thermal properties, convective heat transfer coefficient, Nusselt number, Friction factor, performance index, pumping power and efficiency of loop are investigated. An enhancement in thermal conductivity of PGGNP was observed in between 20% and 32% compared to base fluid. It was found that the PGGNP-Water has a maximum of 119% higher heat transfer coefficient compared to base fluid at 0.1 wt.%. The performance index and pumping power showed the positive effect. The results indicated that both Nusselt number and friction factor of the nanofluid increase with increasing particle volume concentration and Reynolds number. It appears that PGGNP-Water 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

The critical demand for highly efficient thermal transport solution has become a major challenge for industries particularly in the monarchy of energy and power supply [1–3]. This lies from the fact that many physical processes in industries involve transportation of heat between different energy conversion devices in order to harness its useful energy for fulfilling the technological demand [4–9]. At the core of heat transport system, specific priority has been given to address the limitation on the medium employed to complete the energy conversion process. Usually, water has been used as heat carrier especially in oil and gas refinery plants, nuclear and coal based electrical power plants and centralized cooling and heating systems [1,10–13].

The reason being that water is plentiful, inexpensive and readily available in its processed form without requiring additional chemical synthesis prior to its usage. The purification and post treatment processes are relatively straight forward and do not require special protocols for handling and disposing it back to the catchment areas [12,14–16]. However it was also recognized that this material suffers from several drawbacks, particularly on the aspect of its heat transfer properties. Assessment on its thermophysical properties revealed inherently low thermal conductivity that contributed to the major obstacle in attaining high level of heat exchange. Theoretically a thermal conductivity which is generally understood as the level of heat conducting rate of the material should be ideally high to promote heat transfer between heat source and heat sink [17–19]. Low thermal conductivity of water implies increase in thermal resistance by which the heat exchange medium would act as insulator, compromising efficient heat conduction process [20]. This inhibition has prompted the researchers to explore innovative approaches such as modification of heat exchanger surface and configurations, resizing of heat exchanger unit as well as adjusting operating flow conditions as ways to boost the heat transfer efficiency [4,21,22].

In 1995 Choi and Eastman [23] have successfully demonstrated the addition of controlled amount of sub-micron size, high thermal conductivity ceramic based material in aqueous solution that produced a significant improvement to the overall thermal conductivity of the colloidal system relative to the host solution. They coined the formation of stable suspension of these minute particles in heat transfer liquid as 'Nanofluid'. These findings have elucidated promising implication to the theoretical understanding on heat conduction mechanism of

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* Corresponding authors.
E-mail addresses: solangi.quest@gmail.com (K.H. Solangi), salimnewaz@um.edu.my (S.N. Kazi).

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Nomenclature

C_p	Specific heat, J / g K
D	Diameter, m
h	Heat transfer coefficient, W / m^2 K
K	Thermal conductivity, W / m K
L	Tube length, m
m°	Mass flow rate, kg / s
Nu	Nusselt number
Pr	Prandtl number
q	Heat flux, W / m^2
Q	Heat transfer rate, W
Re	Reynolds number
T	Temperature, °C
U	Velocity, m / s
A	Cross-section of the tube (m^2)
f	Friction factor
n	Number of tube passes
G	Mass velocity ([kg/m^2s])
W	Pumping power
Greek symbols	
ρ	Density, kg / m^3
μ	Viscosity, Pa·s
ε	Performance index
Δp	Pressure drop (Pa)
η	Efficiency of loop
Subscripts	
bf	Base fluid
nf	Nanofluid
p	Particles
w	Tube Wall
in	Inlet
out	Outlet
b	Bulk fluid
ID	Inner diameter
Tb	Bulk temperature
OD	Outer diameter

colloidal system as well as its role on penetrating the persisting boundaries on heat transfer subjects [24,25]. This pivotal research has inspired the long time ambition for achieving much compact but high efficiency heat exchanger unit that would match the rapid increase in processing capacity of integrated circuit technology for instance. Since then, a booming of research efforts has seen exponential growth on the number of nanofluid related publications [26–28]. The researches were classified into three main subjects: (1) addressing the role of quantum mechanics on describing the nanofluid property enhancement [4,18,29–32], (2) exploring different materials along with other mechanistic effects such as concentration, particle morphological structure, state of suspension stability and external excitation on tailoring the thermal conductivity of nanofluids [1,33,34] and (3) unraveling the role of nanofluid in enhancing the heat transfer performance in boiling and convection physical processes [4,35–39]. Studies have shown that nanofluid demonstrate novel characteristics previously not found in base fluid alone namely strong temperature dependent thermal conductivity, substantial enhancement of thermal conductivity at very low particle loading, anomalous increase in critical heat flux in pool boiling and prominent increase in heat transfer coefficient at low concentration and beyond the increase on thermal conductivity alone [16,40–44].

Recently, significant investigations on the use of carbon-based nanomaterials such as, single-wall carbon nanotube, multi-wall carbon nanotube, graphene oxide and graphene nanoplatelets (GNPs) to make nanofluids were reported in the literature [8,20]. New research specifies that graphene nanofluids could provide higher thermal conductivity enhancement in comparison to other tested nanofluids [20]. Graphene is an allotrope of carbon atoms which has drawn attention of researchers recently due to its superior properties, such as high elastic modulus, good electrical conductivity, good thermal conductivity, and self-lubricating behavior [45–47]. Baby and Sundara [48] synthesized and prepared copper oxide decorated graphene hybrid (CuO-HEG) nanofluid and obtained 28% enhancement in thermal conductivity for 0.05% volume concentration of functionalized graphene without any surfactant. In their work, GNP-nanocomposite powder was synthesized by chemical reaction process. GNP was functionalized by acid treatment method and further decorated with silver. After that GNP–Ag/water hybrid nanofluids were made by dispersing the nanocomposite material in distilled water. Jha and Ramaprabhu [49] investigated the influence of well-dispersed copper nanoparticles-loaded multi-walled carbon nanotubes (Cu-MWCNTs) in deionized water (DI-water) and Cu-MWCNTs in EG on the thermal conductivity and reported a marked enhancement at a very low volume fraction, which was attributed to the homogeneous dispersion of Cu-MWCNTs in the base fluids and formation of hydrophilic MWCNTs. In a similar study, the thermal conductivity and heat transfer enhancements of MWCNT-based water nanofluids were investigated and a noticeable enhancement was reported that was attributed to the thinning of the thermal boundary layer by MWCNTs and reducing the thermal resistance [50,51]. However, among various carbon-based nanostructures, graphene-family nanomaterials (GFNs) appear to have over or more potential due to their attractive thermal, electrical and mechanical properties [52–55]. Indeed, GFN has found many applications including its use as a high performance coolant. A number of theoretical and experimental studies showed that GFN has a rather high thermal conductivity [8,56], indicating its superb potential as an effective for applications in thermal equipment such as thermosyphone and car radiators [52,53]. Recently, large-scale production of GNP via ball milling method provided the opportunity for their use in many industrial applications. Amiri et al. [57] prepared the ethylene glycol-treated GNP by introducing the mass production method. They synthesized the car radiator coolant in the presence of neutral media, where car engine can work at lower temperature via a high performance unit. The ratio of convective to conductive heat transfer was unique. They introduced new economical product with high performance index.

The GNP is a 2D material that has attracted much of interest due to its excellent mechanical, electrical and thermal properties; the thermal conductivity of GNP is reported to be as high as 3000–5000 W/m-K [2,15]. Further, the heat transfer properties of GNP are expected to be much different from zero dimensional nanoparticles and one dimensional carbon materials. GNP is an excellent thermal conductor, so a GNP nanofluid is expected to display a significant thermal conductivity enhancement. In addition, synthesizing graphene nanoparticles is relatively easy and cost effective. A small variation of properties of graphene has been reported due to different methods used to manufacture one layer or multi-layer graphene such as, exfoliation of graphene oxide layer, deposition with chemical vapor and mechanical cleavage. Experimental investigation has revealed that the thermal conductivity and heat transfer properties of one layer graphene are higher than CNT. Two-dimensional honey comb lattice graphene with more than 10 layers called graphene nanoplatelets (GNPs). Dispersion of graphene with good stability is one of the big issues that must be solved. So by using functionalization method (acid treat and amino function), proper ultrasonic and solvent it could be able to prepare stable dispersed graphene based nanofluids [8]. Much research has been reported on the thermophysical properties of GNP nanofluids, but little has been performed on the convective heat transfer characteristics of GNP nanofluids. Additional studies and investigations on convective heat transfer are required to apply nanofluids in heat transfer systems [45,58–62].

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