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Measurement and modeling of thermal conductivity of graphene nanoplatelet water and ethylene glycol base nanofluids

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ABSTRACT

Three graphene nanoplatelet (GNP) nanofluids with different base fluids, viz. ethylene glycol (EG), deionized water (DW), and EG/DW (1:1) were prepared and characterized. The stability of GNP nanofluid was analyzed. Thermal conductivity was tested over the temperature range −20 °C to 50 °C. A new model is proposed for the effective thermal conductivity of the GNP nanofluid considering Brownian motion, length, thickness, average flatness ratio and interfacial thermal resistance of GNP, and it was compared with Maxwell, H-C and Chu models. The maximum thermal conductivity enhancement of EG, EG/DW (1:1) and DW based nanofluid is 4.6%, 18% and 6.8% respectively. Interestingly, the thermal conductivity of EG based GNP nanofluids does not show appreciable enhancement. The thermal conductivity enhancement of EG/DW (1:1) GNP nanofluid is greater than that of pure EG GNP nanofluid. In particular, the enhancement ratio at subzero temperature is larger than that at higher temperatures. The new model and Chu model are in agreement with the experimental data, and the new model is more rational for the GNP nanofluids. The new model shows that the influence of Brownian motion of GNP on thermal conductivity is significant at higher temperatures, higher concentration and smaller nanoparticles.

1. Introduction

Nanofluids, originally proposed by Choi and Eastman in 1995 [1], are produced by suspending nanoparticles in a conventional fluids and the stable nanoparticles in nanometer size less than 100 nm. Nanofluids can be prepared in one-step or a two-step process [2]. Nanofluids have been investigated as a kind of Jeffrey fluid and non-Newtonian fluid extensively owing to the anomalous thermal transport characteristics which show great potential for several industrial applications [3–15]. Nanofluids have been the subject of numerous scientific studies [16,17]. Among their numerous industrial applications are: systems of engine cooling [18], electronic device cooling [19–21], solar energy devices [22–25], nuclear reactor [26–28], heating and cooling system for buildings [29], etc.

The properties of different carbon nanomaterials have been studied, such as diamond nanoparticles [30], graphite nanoparticles [31] and carbon nanotubes [32,33]. Graphene, first discovered by Novoselov et al. [34], is used in nanofluids extensively owing to the distinct thermal properties. Thermal conductivity of graphene can be 5200 W/m K according to Balandin et al. [35], which displays its superiority to carbon nanotubes [36]. Yu et al. [37] researched the thermal conductivity of graphene and ethylene glycol nanofluids, and discovered that thermal conductivity enhancement was 86% at 5 vol% of graphene nanoplatelet (GNP). Baby and Ramaprabhu [38] investigated the enhanced convective heat transfer of graphene nanofluids and found enhancements of 16% and 75% in thermal conductivity at 0.05 vol% of GNP in water base fluid at 25 °C and 50 °C respectively. Thermal conductivity enhancement was up to 27% for 0.02 vol% concentration at 45 °C. But the low enhancement of thermal conductivity of graphene-EG nanofluid was only about 2.4% and 7.5% for 0.05% and 0.08% volume fraction at 50 °C, respectively.

Jyothirmayee et al. [39] carried out study on the enhancements in electrical and thermal conductivity of EG and deionized water (DW) containing (0.008–0.138) vol% GNP at (25–50) °C. The thermal conductivity measurement showed about 6.5% and 13.6% enhancements at 25 °C for the 0.14% volume fraction of GNP in EG and DI water, respectively. Emad Sadeghinezhad et al. [40] studied the effective thermal conductivity of the Water-GNP (0.025–0.1 wt%, 15-40 °C) nanofluid, they found that the thermal

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Nomenclature

A	surface area of the particle, m^2
c_p	thermal capacity, J/K
d	diameter, m
G	Green function
k	thermal conductivity, W/m K
k_B	Boltzmann constant, 1.381×10^{-23} m^2 kg s^{-2} K^{-1}
K^*	effective thermal conductivity of composite, W/m K
K^0	constant thermal conductivity of homogeneous medium, W/m K
K_m	thermal conductivity of matrix, W/m K
$K'(r)$	thermal conductivity of arbitrary fluctuating part, W/m K
L	length of particles, m
M	transition matrix
n	empirical shape factor
R_k	interfacial thermal resistance, m^2 K/W
r_c	mean radius of gyration, m
T	temperature, K
t	thickness of particles, m
v	volume, m^3

Greek

β	fraction of liquid
Φ	volume fraction of the particles
Φ_m	mass fraction of the particles
ψ	sphericity
η	average flatness ratio of GNP
ρ	density, kg/m^3
σ	uncertainty
μ	dynamic viscosity, Pa s

Subscripts

Brown	Brownian motion
E	enhancement
eff	effective
EMT	effective medium theory
eq	equivalent
f	base fluid
non-sph	non-spherical particles
p	particle

Abbreviations

DW	deionized water
EG	ethylene glycol
GNP	graphene nanoplatelet

conductivity increases as temperature increased in all cases. The thermal conductivity enhancement was between 7.96% and 25%. Ali Ijam et al. [41] observed the largest enhancement for the graphene-water nanofluid was 10.3% which appeared at 45 °C and 0.02 vol%. Gupta et al. [42] tested thermal conductivity of GNP-water nanofluid. They discovered that the maximum enhancement was 12% and 27% for 0.05 vol% and 0.2 vol% concentration at 50 °C, respectively. But the enhancement was no more than 4% for 0.025 vol% at 45 °C.

As an efficient heat transfer working fluid, graphene nanofluids should be very useful in cooling hydrogen engine which has many key issues such as backfire and pre-ignition etc. [43]. Moreover, for industrial application of the graphene nanofluid in engine cooling, the system temperature range must extend to subzero temperature. However, the thermal conductivities of various GNP nanofluids at subzero temperature have not been reported. For developing a suitable cooling media which can be employed in hydrogen engine cooling, and especially in the subzero temperature range, experimental studies of thermal conductivities of GNP nanofluids containing different base fluid: EG, EG/DW (1:1) and DW are carried out in this work.

Several comprehensive reviews are available covering both experimental and modeling of thermal conductivity of nanofluids of diverse nanoparticles suspended in different base fluids including effects of shape, aspect ratio, particle size, orientation and concentration as well as temperature [44–51]. Here we will mention only recent studies on graphene nanofluids.

Literature reviews show that there are many discrepancies in published data about enhancements of thermal conductivities of graphene nanofluids. This is expected as there are many complicating factors impacting the thermal conductivity of nanofluids, such as GNP structure and concentration, graphite type and so on [52]. On the basis of Nan's model [53], the Chu model [54] considered the length, layer thickness, flatness ratio and interfacial thermal resistance of GNP, which includes more morphology factors explicitly. However, effective medium theories with the microscopic static mechanisms assume that particles are stationary in a fluid, which neglects the effect of the Brownian motion of GNP, which is considered a limiting factor for the thermal conductivity enhancement of nanofluids [55–59]. But molecular dynamics simulations investigated by Evans et al. show that the enhancement owing to Brownian motion of nanoparticles is rather unimportant [60]. Sarkar and Selvam [61] also carried out molecular dynamics simulations, and they observed that the enhancement of thermal conductivity is mainly owing to the increased movement of liquid atoms in the presence of nanoparticles. Consequently, there is lots of disagreement on the influence of Brownian motion of nanoparticles by different molecular dynamics models.

To summarize, for GNP-based nanofluids, existing models does not explicitly explain the impacts of GNP on the effective thermal conductivity. A new model considering the heat transfer mechanisms induced by GNP Brownian motion, the GNP morphology and the base fluid is proposed in this work. A comparison of the new model with Maxwell and Hamilton - Crosser (H-C) is made for the GNP nanofluid systems, examined here.

2. Experimental apparatus and procedure

2.1. Preparation and characterization of GNP nanofluids

The GNP nanofluids were created by two-step method [2] without surfactant. Different mass of graphene nanoplatelet (GNP) (Hengqiu Graphene Science and technology Ltd. Co. Suzhou, China), 6–10 layers, dimensions 5–50 μm, was readily dispersed in deionized water (DW), EG/DW (volume ratio 1:1) and ethylene glycol (EG) respectively, after 60 min of high-powered ultrasonication, forming stable GNP nanofluids with different concentrations (range from 0.05 wt% to 0.15 wt%).

Fig. 1 shows SEM for GNP nanofluid, for which the GNP aggregates were broken into smaller and thinner nanoplatelets after ultrasound irradiation for 60 min. To ensure the purity of GNP nanofluids, UV–visible absorption spectrum analysis was carried out (Fig. 2). The SEM shows maximum absorption at 270 nm which refer to π-π∗ transition of C-C. The value shows a good agreement