Journal of Colloid and Interface Science 509 (2018) 140–152

Contents lists available at ScienceDirect

Journal of Colloid and Interface Science

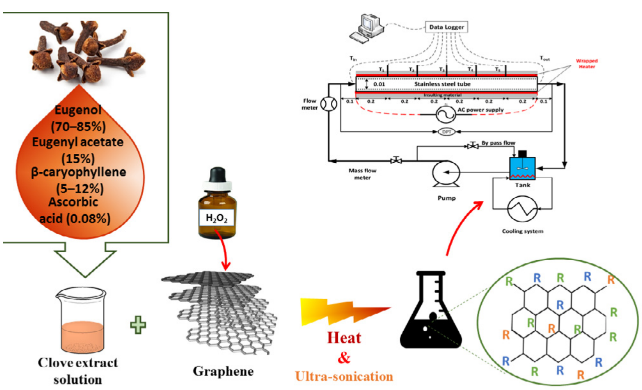
journal homepage: www.elsevier.com/locate/jcis

A facile, bio-based, novel approach for synthesis of covalently functionalized graphene nanoplatelet nano-coolants toward improved thermo-physical and heat transfer properties

Rad Sadri [a,*], Maryam Hosseini [a,*], S.N. Kazi [a,*], Samira Bagheri [c], Ali H. Abdelrazek [a], Goodarz Ahmadi [b], Nashrul Zubir [a], Roslina Ahmad [a], N.I.Z. Abidin [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia
[b] Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY 13699, USA
[c] Nanotechnology & Catalysis Research Centre (NANOCAT), IPS Building, University Malaya, 50603 Kuala Lumpur, Malaysia

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 January 2017
Revised 13 July 2017
Accepted 15 July 2017
Available online 17 July 2017

Keywords:
Eco-friendly synthesis
Functionalization
Nanofluids
Thermo-physical properties
Carbon nanoparticles
Graphene nanoplatelets (GNPs)
Convective heat transfer

ABSTRACT

In this study, we synthesized covalently functionalized graphene nanoplatelet (GNP) aqueous suspensions that are highly stable and environmentally friendly for use as coolants in heat transfer systems. We evaluated the heat transfer and hydrodynamic properties of these nano-coolants flowing through a horizontal stainless steel tube subjected to a uniform heat flux at its outer surface. The GNPs functionalized with clove buds using the one-pot technique. We characterized the clove-treated GNPs (CGNPs) using X-ray photoelectron spectroscopy (XPS) and transmission electron microscopy (TEM). We then dispersed the CGNPs in distilled water at three particle concentrations (0.025, 0.075 and 0.1 wt%) in order to prepare the CGNP-water nanofluids (nano-coolants). We used ultraviolet–visible (UV–vis) spectroscopy to examine the stability and solubility of the CGNPs in the distilled water. There is significant enhancement in thermo-physical properties of CGNPs nanofluids relative those for distilled water. We validated our experimental set-up by comparing the friction factor and Nusselt number for distilled water obtained from experiments with those determined from empirical correlations, indeed, our experimental set-up is reliable and produces results with reasonable accuracy. We conducted heat transfer experiments for the CGNP-water nano-coolants flowing through the horizontal heated tube in fully developed turbulent condition. Our results are indeed promising since there is a significant enhancement in the Nusselt number and convective heat transfer coefficient for the CGNP-water nanofluids, with only a negligible increase in

* Corresponding authors.
E-mail addresses: rod.sadri@gmail.com (R. Sadri), hoseini.sma@gmail.com (M. Hosseini), salimnewaz@um.edu.my (S.N. Kazi).

http://dx.doi.org/10.1016/j.jcis.2017.07.052

the friction factor and pumping power. More importantly, we found that there is a significant increase in the performance index, which is a positive indicator that our nanofluids have potential to substitute conventional coolants in heat transfer systems because of their overall thermal performance and energy savings benefits.

1. Introduction

Energy management is a major concern in various technological applications such as cooling devices, solar collectors and heat exchangers. However, the poor thermal conductivity of conventional coolants (*e.g.* oil, propylene glycol, ethylene glycol and water) limits the effectiveness and applicability of these coolants in heat transfer systems. Hence, scientists and researchers are actively searching for ways to develop alternative coolants with higher thermal conductivity in order to boost the heat dissipation efficiency of the thermal systems. One of the innovative ways to improve the thermal conductivity of coolants is to disperse solid nanoparticles with high thermal conductivity within the base fluid [1–6]. This new generation of conductive fluids containing well-dispersed nanoparticles are known as nanofluids [7,8]. Various nanoparticles such as carbon nanomaterials and metal-oxides (copper oxide (CuO), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3) and silicon dioxide (SiO_2)) have been utilized to produce nanofluids with superior thermal conductivity. Recent studies have shown there is superior improvement in the heat transfer, rheological and thermo-physical properties of carbon-based aqueous suspensions [9–14]. Wang et al. [15] estimated the viscosity of various nano-coolants produced by dispersing CuO and Al_2O_3 nanoparticles in ethylene glycol, DI water, engine oil and vacuum pump fluid. The results showed that the viscosity increases by 30% for the Al_2O_3-water nanofluid containing 3 vol% of Al_2O_3 nanoparticles. Suresh et al. [16] experimentally studied the friction factor and convective heat transfer properties of Al_2O_3 aqueous suspensions flowing through a tube with plain or spiral rod inserts under constant heat flux and laminar flow conditions. The maximum enhancement in Nusselt number was achieved for the nanofluid containing 0.5% of Al_2O_3 nanoparticles flowing through a tube with spiral rod inserts, with a value of 24%. In addition, the isothermal pressure drop for the Al_2O_3-water nanofluids flowing through the tube with spiral rod inserts was higher than that for plain tube by 5–15%. Syam Sundar et al. [17] conducted theoretical and experimental study on the effective thermal conductivity and viscosity of magnetic Fe_3O_4 aqueous suspensions. They observed that there was an increase in the thermal conductivity and viscosity of the nano-coolants by increasing the particle volume concentration. Moreover, the viscosity enhancement of the nanofluid was higher than its thermal conductivity enhancement at the same particle volume concentration and temperature. Among the various types of nanoparticles, multi-walled, double-walled and single-walled carbon nanotubes (CNTs) have attracted much interest among scientists and researchers, particularly one-dimensional carbon nanostructures and two-dimensional carbon nanostructures (graphene nanoplatelets). This is due to their favourable thermal, electrical and mechanical properties [18], rendering these CNTs suitable for heat transfer enhancement. Choi et al. [19] achieved a thermal conductivity enhancement of 160% for carbon nanotubes dispersed in synthetic poly(α-olefin) oil at particle volume concentration of 1.0%. Bobbo et al. [20] studied the viscosity of SWCNT-water nanofluid and TiO_2-water nanofluid and obtained a viscosity enhancement of 12.9 and 6.8%, respectively. This viscosity enhancement was achieved at particle concentration of 1.0 vol% for both types of nanofluids. Sadri et al. [21] studied the effect of sonication time on the dynamic viscosity, thermal conductivity as well as dispersion of MWCNT nanofluids. They observed that there was a decrease in the viscosity whereas there was an increment in the thermal conductivity for these nano-coolants by enhancing the temperature and sonication time. The maximum thermal conductivity enhancement was 22.31% (ratio of 1.22) at a sonication time and temperature of 40 min and 45 °C, respectively. Syam Sundar et al. [22] investigated the friction factor and heat transfer properties of MWCNT-Fe_3O_4 nanocomposite aqueous suspensions flowing through a tube with longitudinal strip inserts. The results illustrated that the Nusselt number increases by 32.72% for the 0.3% nanofluid flowing through the tube without inserts. However, the Nusselt number increases by 50.99% for the nanofluid flowing through the tube with inserts (aspect ratio: 1) at a Reynolds number of 22,000. Graphene nanoplatelets (GNPs), composed of two-dimensional atomic sp^2 carbon layers, have garnered much interest from scientists and researchers in recent years owing to their outstanding characteristics such as excellent thermal conductivity and high specific surface area [23]. For this reason, GNPs appear to be a promising additive for various types of applications such as inkjet printing, conductive thin films, solar cells, polymer composites, aerogels and heat exchangers [24,25]. However, the outstanding properties of nanofluids cannot be attained by simply mixing a base fluid with nanoparticles. Despite the high specific surface area of graphene, graphene tends to agglomerate due to the strong π-π stacking interactions. In addition, the dispersibility of graphene in aqueous media is one of the most critical parameters in heat transfer systems [26]. Thus, various techniques (both physical and chemical routes) have been proposed to enahance the dispersibility of graphene in organic and aqueous media. In general, these techniques involve non-covalent and covalent functionalization of graphene [27]. Covalent functionalization is typically used to attain high dispersion of carbon nanomaterials in aqueous media. In this technique, the hydrophilic functional groups such as carboxyl acids, amine, esters and alkali groups are attached onto the surface of the GNPs using either one of the following techniques: oxidation, addition of radicals or reduction of alkali metals [28,29]. Free radical coupling appears to be the most appealing functionalization technique for carbon nanostructures since it provides a facile means for covalent functionalization. In this technique, peroxides and substituted anilines [30,31] are used as the starting materials. However, there a few issues associated with all of the aforementioned techniques such as corrosion of equipment, costly materials as well as environmental issues. Thus, it is more crucial than ever to develop a functionalization method for carbon nanostructures that is both economical and environmentally friendly [32].

Cloves are among the most widely cultivated spices in regions with tropical climate. Clove buds are primarily composed of phenolic compounds such as eugenyl acetate (15%), eugenol (70–85%) and β-caryophyllene (5–12%). Clove buds also contain trace amounts of ascorbic acid (0.08 wt%) [33]. The favourable properties and structure of cloves make these spices ideal to enhance the functionalization of GNPs in aqueous media. Hereupon, the main objective of our research is to develop an environmentally friendly, cost-effective and industrially scalable method for synthesizing GNPs covalently functionalized with cloves (CGNPs). We also