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Toward improved engine performance with crumpled nitrogen-doped graphene based water–ethylene glycol coolant

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HIGHLIGHTS

- Synthesizing wrinkled crumpled nitrogen-doped graphene with high surface area.
- Functionalization analysis with XPS, Raman and TEM.
- Investigation of thermo-physical and electrical properties.
- Investigation of the forced convective heat transfer.

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ABSTRACT

Crumpled nitrogen-doped graphene nanosheet (CNDG) is considered a promising carbon-based nanosheet due to its high surface area, superior electrical, thermal and mechanical properties. Herein, CNDG is first prepared and tested as an additive for preparing a new engine coolant. The prepared two-dimensional CNDG feature high electrical conductivity, excellent thermal conductivity and heat transfer properties, permitting the CNDG-based water-ethylene glycol coolants to exhibit excellent Mouromtseff number, electrical properties and heat transfer performance for all temperatures and weight concentrations in a car radiator. Further, steady-state forced convective heat transfer experiments have been performed to evaluate the cooling capabilities of the prepared coolants.

1. Introduction

Heat transfer is an essential part of wide range of fields and industries e.g. oil and gas, electrical, food and nuclear, automotive industries, etc. Among different industries, automotive industries is one of the world's most important economic sectors by revenue and has a special effect on the other industries. Growing highly efficiency engines for automotive industries is one of the most important goal of automotive industries. Increasing the thermal efficiency of radiator by optimizing the size [1–3], addition of fins, and use of micro-channels have been suggested and employed [4]. However, there are some limitations in applying many of the conventional methods, such as lack of space, for increasing the cooling rate [5]. On the other hand, conventional base-fluids such as water and ethylene glycol (EG) have poor thermal conductivity, which intensify the reduction of engine yield [6]. To solve this issue, highly performance heat transfer fluids can be utilized in the car radiators.

To enhance the heat transfer properties of conventional base-fluids and heat transfer rate in heat exchangers, addition of different particles, in particular carbon nanostructures such as carbon nanotubes (CNT) [7–9], graphene nanoplatelets (GNP) [6] and few-layered graphene (Gr) [10], has been suggested as a promising approach [11–16].

Jha and Ramaprabhu [17] studied the influence of Cu-loaded carbon nanotubes (Cu-CNTs) in deionized water (DI water) and Cu-CNTs in EG on the thermal conductivity. They obtained a significant enhancement at a very low volume fraction, which attributed to the well-dispersibility of Cu-CNTs in the working fluids as well as the formation of hydrophilic CNT. A similar study conducted by this group showed that the thermal conductivity and heat transfer rate enhancements of CNT-based water nanofluids noticeable and the reason was attributed to the thinning of the thermal

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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
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
Pr	Prandtl number
q	heat flux, W/m^2
Q	heat transfer rate, W
Mo	Mouromtseff number
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^2 s)

Greek symbols

ρ	density, kg/m^3
μ	viscosity, Pa s
ε	performance index
Δp	pressure drop (Pa)

Subscripts

bf	basefluid
nf	nanofluid
p	particles
w	tube Wall
in	inlet
out	outlet
b	bulkfluid

boundary layer by CNT and resulted in reducing the thermal resistance [18,19].

The intrinsic heat transfer capacity of the carbon nanostructure could be considered as the main factor for thermal improvement. For working fluids including carbon nanostructures such as CNT and Gr, the chemical surface effects and surface area of carbon nanostructures can dominate the extent of energy transfer in prepared coolants with this type of nanostructures [20,21]. They concluded that liquid molecules form layers around the carbon nanostructures, thus increasing the local ordering of the liquid layer at the interface region. It is obvious that the liquid layers at the interface would fairly have a higher thermal conductivity than the bulk liquid. Therefore, in addition to the effect of Brownian motion of carbon nanostructures, the prepared nanolayer around nanostructures play a vital role in enhancing the thermal conductivity of carbon nanostructures-based nanofluids [21,22].

Layering of basefluid molecules on the surface of nanoparticles in a nanofluid should be studied using nuclear magnetic resonance (NMR). Xue et al. [23] and Buongiorno et al. [24] showed that the thermal transport in layered liquid had no effect on the heat transfer characteristics and it is not be adequate to explain the increased thermal conductivity of suspensions included nanoparticles. In order to elucidate the reasons for the strange growth of the thermal conductivity in nanofluids, Keblinski et al. [25] and Eastman et al. [26] suggested four potential mechanisms e.g. molecular-level layering of the liquid at the liquid/particle interface, Brownian motion of the nanoparticles, the nature of heat transport in the nanoparticles, and the effects of nanoparticle clustering. They suggested that the effect of Brownian motion can be neglected since influence of thermal diffusion is higher than Brownian diffusion. However, they only measured the cases of stationary nanofluids. Wang et al. [27] concluded that the thermal conductivities of nanofluids is a function of the particle structure and microscopic motion (Brownian motion and inter-particle forces). Also, some researches show that having high surface area with nanoparticles can be considered as one of the positive properties for higher heat transfer rate in the presence of nanofluids. Thus, carbon nanostructures with high surface area can provide better condition for enhancing heat transfer rate and thermal conductivity of working fluid. To reach a carbon nanostructure with high surface area and for preparing high-performance heat transfer coolant, modification of graphene should be elaborately designed by taking the morphology and pore structure into consideration. It is also noteworthy that N-doping performs an important role in regulating the electronic, thermal and chemical properties of carbon materials because of the similar atomic size and the availability of five valence electrons to form strong valence bonds with carbon atoms. Nitrogen-doped graphene materials with large mesopores favorable for heat transfer were found to exhibit a good coolant property as an additive and significantly well-dispersed suspension [28]. The higher electronegativities of N ($x = 3.04$) than that of C atoms ($x = 2.55$) in N-doped graphene resulted in a significant surface charge state of nanoparticles, leading to the excellent stabilized colloidal suspension [29]. A significant enhancement in thermal conductivity as well as in electrical conductivity of dispersed NDG in the ethylene glycol (EG) [28] confirms its potential application towards nanofluids. Although various studies conducted on the thermal and electrical conductivity of composite material suspensions, no investigation has yet performed on the nanofluids containing crumpled N-doped graphene in water–EG media. The crumpled nitrogen-doped graphene (CNDG) seems to meet both above-mentioned criteria and thus is attractive and novel for coolant applications.

To this end, an efficient and facile method for fabricating highly crumpled nitrogen-doped graphene nanosheets (CNDG) with a high surface area is employed here to reach a carbon nanostructure with above-mentioned properties. The CNDG samples are then analyzed from the viewpoint of functionality, and morphology. Due to the abundant wrinkled structures, high surface area and electrical conductivity, thermophysical and electrical properties of coolants containing CNDG are significantly increased. With this observation, the cooling potentials of synthesized coolants have been investigated in terms of the steady-state forced convective heat transfer. In addition, physical insight were prepared to clarify the improved heat transfer coefficient of CNDG-based water–ethylene glycol coolant (CNDG-WEG).

2. Experimental

2.1. Material and methods

Preparation of CNDG was performed according to the technique reported by Wen et al. [30]. To prepare CNDG, first graphene oxide (GO) was prepared by using Hummers method. Typically, 10.0 ml cyanamide (NH_2CN) was poured into 100 ml GO solution (1 mg/ml) under stirring. The obtained solution was then heated at