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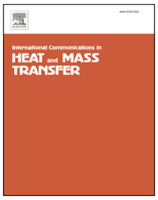

Evaluation of viscosity and thermal conductivity of graphene nanoplatelets nanofluids through a combined experimental–statistical approach using respond surface methodology method☆

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ABSTRACT

In the present study, three influential parameters including concentration, temperature and specific surface area of graphene nanosheets were investigated, which is the effective parameters on the viscosity and thermal conductivity of aqueous graphene nanosheets (GNP) nanofluids. A mathematical model developed by respond surface methodology (RSM) based on a central composite design (CCD). Also, the significance of the models was tested using the analysis of variance (ANOVA). The optimum results of aqueous GNP nanofluid showed that the concentration has a direct effect on the relative viscosity and thermal conductivity. Furthermore, predicted responses proposed by the Design Expert software were compared with the experimental results. The statistical analysis of the predicted values was in satisfactory agreement with the empirical data and was performed the excellent predictability of the proposed models.

1. Introduction

Nanofluids, comprising highly thermally conductive nanoparticles dispersed in a quiescent fluid at low volume fractions, will probably be the future heat transfer media [1–5]. Different mechanisms have been proposed for effective thermal conductivity enhancement (ETCE) of nanofluids: Brownian motion of nanoparticles, molecular layering, the nature of heat transport in nanoparticles, particle interface [6–10], nanoparticle aggregation, clustering and specific surface area [11]. Theoretically, the nanoparticles are very efficient in enhancing the performance of thermal applications. Recent studies show that nanofluids are able to enhance thermal efficiency; however, there are some restrictions, such as instability, agglomeration, erosion and corrosion of thermal equipment systems. Apparently, by choosing the adequate shape, type and size of nanoparticles, most of the desired thermophysical properties can be achieved [12–15].

Viscosity of the adjacent layer of fluid offers frictional resistance against shearing stresses. One of the most critical parameters in nanofluids is viscosity, which plays a very important role to determine the quality of heat transfer [16]. Viscosity of nanofluids generally increases with increase in concentration of nanoparticles and decreases with temperature. Lee et al. [17] explored that particle to particle interaction is responsible behind nonlinear relation between viscosity and volume concentration. Studies performed by many researchers suggested that apart from particle size and volume concentration, the temperature of working fluid also plays an important role in viscosity variation [12,18–20]. Azmi et al. [21] indicated that the increases in nanofluid temperature affect nanofluid viscosity.

Thermal conductivity of nanofluid is one of the crucial factors, which governs heat transfer capability of nanofluids in various thermal applications. Hence, a number of mathematical model according to the experimental data and theoretical analysis about the thermal conductivity of nanofluid have been done by many researchers over the last two decades [22]. A lot of studies indicated that desired thermal conductivity of nanofluid can be achieved by selecting the concentration, temperature, proper size, shape and type of nanoparticles and base fluid materials [23,24].

Many researches were done for enhancement of the thermal properties of conventional fluids by adding many types of nanoparticles at different [25–27]. Nowadays, researches have been devoted to studies on the use of carbon-based nanostructures like graphite [28], graphene oxide [29], graphene [30], carbon nanotubes (CNT) [31], single-wall carbon nanotubes (SWCNT) [32] and multiwall carbon nanotubes (MWCNT) [18] to prepare nanofluids. In recent years, most investigations on thermal conductivity of carbon nanostructure have been performed with higher heat transfer compared to the metal oxides.

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Table 1
GNP nanosheets specifications.

Property	Specification
Color	Black granules/powder
Carbon content	>99.5
Bulk density	0.2–0.4 g/cm^3
Relative gravity	2.0–2.25 g/cm^3
Specific surface area	500 and 750 m^2/g
Particle diameter	2 μm
Thickness	2 nm
Thermal conductivity (parallel to surface)	3000 W/m K
Thermal conductivity (perpendicular to surface)	6 W/m K

For instance, multi-walled carbon nanotube exhibited 3000 W/m K for thermal conductivity [33] while this value is about 40 W/m K for Al_2O_3.

Latest research reveals that graphene as a single layer of hybridized SP^2 carbon atoms arranged in a honeycomb lattice has a high thermal conductivity [34]. Graphene nanoplatelets (GNP) are one carbon atom conducted to three carbon atoms in one plate with equal angle and two-dimensional (2D) crystals that are expected to be different from the one-dimensional carbon nanotubes and zero-dimensional nanoparticles in terms of heat transfer properties. Graphene nanoplatelets (GNP) attract scientist's attention these days due to their thermal conductivity that is recorded to be as high as 5000 W/m K [2,12,33]. Therefore, due to the unique properties of GNP especially an excellent thermal conductivity, to be expected graphene-based nanofluids are normally display a significant thermal conductivity enhancement [3,35].

Recently, researchers have been encouraged to estimate and predict accurately variables such as viscosity and thermal conductivity of nanofluid in different temperature, particle diameters, density, sonication time and concentration by using soft computing methods. A. Kazemi-Beydokhti et al. [36] have determined the most important variables on thermal conductivity of CuO nanofluid using the fractional factorial design approach. Hemmat esfe et al. [37] model the dynamic viscosity and thermal conductivity of ferromagnetic nanofluid using artificial neural network.

Several statistical methods have been proposed to minimize the experimental measurement and provide correlations for predicting the variables of nanofluids such as genetic algorithms, fuzzy logic and respond surface methodology, etc. A classical experimental design method, which is not only time-consuming and laborious but also expensive in terms of its considerable material. Moreover, the use of traditional methods of experimentation neglects the effects of interaction between factors and leads to low efficiency in process optimization. Therefore, the application of statistical experimental design in nanofluids seems to be the best methodology for optimization.

Response surface methodology (RSM) and factorial design analysis are proper tools to determine the optimal process conditions [38]. In many experimental settings, it is not desirable or feasible to assess all factors and their joint effects; thus it is only the dominant factors that need to be identified. The main aim of this study is to utilize the design of experiment for prediction of viscosity and thermal conductivity of aqueous GNP nanofluids and compare the effect of different important parameters such as specific surface area of GNP nanosheets, various temperatures and concentrations.

Table 2
Variable factors and their specifications.

		Level		
Factor	Unit	(−1) Low	(0) Centre point	(+1) High
Temperature (A)	°C	20	40	60
Concentration (B)	wt%	0.05	0.075	0.1
		Categorical		
Surface area (C)	m^2/g	500		750

2. Materials and method

2.1. Nanofluid preparation

GNP nanosheets with special properties (see Table 1) were purchased from XG Sciences, Inc., USA. The dispersion of GNP nanosheets into the base fluid is an essential process and needs special attention. Based on our previous work [39], the specified amount of GNP nanosheets was measured by an analytical balance (Precisa balance, Switzerland) and then was mixed with distilled water (DW). Therefore, the ultrasonication probe (QSonica, USA) was used to prepare a homogeneous and stable GNP nanofluid with concentrations of 0.05, 0.075, and 0.1 wt%. However, all concentrations of GNP nanofluids were stable for several days after initial preparation.

2.2. Thermo-physical properties measurements

In order to understand the effect of GNP nanosheets on thermal conductivity and rheological properties of base fluid, the thermal conductivity (KD2 pro, USA) and viscosity (Anton Paar rheometer, Austria) tests were conducted for several concentrations and temperatures (see Fig. 1).

2.3. Experimental design

Design-Expert software version 9.0.5 was applied to analyze the statistical results. The impact of three factors, including: temperature (A), concentration (B) and specific surface area of nanosheets (C) was examined by analysis of variance (ANOVA). It is well suited for fitting a quadratic surface using a standard RSM design called a central composite design (CCD), which usually works well for process optimization.

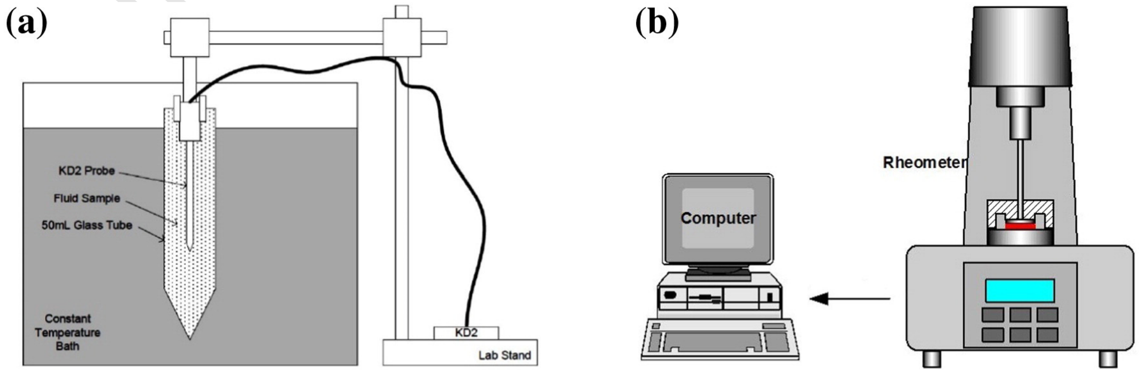

Fig. 1. Schematic diagram of the (a) thermal conductivity and (b) viscosity measurement at different temperature.

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