CI&CEQ
Chemical Industry & Chemical Engineering Quarterly

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Chem. Ind. Chem. Eng. Q. 27 (2) 177–187 (2021) CI&CEQ

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SCIENTIFIC PAPER

UDC 661.666:66.03:54

STUDIES ON THERMOPHYSICAL PROPERTY VARIATIONS OF GRAPHENE NANOPARTICLE SUSPENDED ETHYLENE GLYCOL/WATER

Article Highlights

- Graphene/ethylene glycol/water mixed nanofluids were prepared
- The thermophysical characteristics of the graphene suspended base fluid was studied
- Obtained results were compared with models proposed in the literature

Abstract

The objective of the study is to determine the thermophysical property variations (such as viscosity, density, specific heat capacity and thermal conductivity) of graphene suspended base fluid (ethylene glycol (EG)/water (W)), with respect to graphene nanoparticle concentration and hot fluid inlet temperature. Graphene nanoparticle concentrations (0.2, 0.4, 0.6, 0.8 and 1 vol.%) and the base fluid of 30:70 vol.% of EG: Water is prepared initially. The impact of graphene nanoparticle addition on base fluids based on experimentation in the commercial plate heat exchanger was studied. In this experiment, the hot fluid inlet temperature was varied at 55, 65 and 75 °C. The experimental results of thermophysical properties were compared with the selected models proposed in the literature. Einstein (1956), Kitano (1981) and Bachelor models (1977) have been used to consider the effect of viscosity. The measured density and specific heat capacity were validated with Pak and Cho and Xuan models, respectively. To consider the effect of thermal conductivity, three different models (Maxwell (1954), Vajjah (2010) and Sahoo (2012)) have been used. Study revealed that the thermophysical properties of base fluid significantly affect the graphene nanoparticle suspension.

Keywords: graphene, nanoparticle, thermophysical property, ethylene glycol, water.

Viscosity, density, specific heat capacity and thermal conductivity are significant thermophysical properties, which alter the properties of conventional heat transfer fluids. Viscosity is a significant property which measures a fluid friction and its internal flow resistance. Density of a fluid is directly proportionate with respect to pressure and indirectly proportionate with respect to temperature. Also, this property is important in the stage of preparation of nanoparticle suspensions, since for materials with different densities is difficult to get a homogeneous mixture. Specific heat capacity represents the quantity of heat needed to increase the temperature of one kg of mass by 1 K. It is a significant factor since it decides the requirement of heat transfer fluid. Among the four properties, thermal conductivity is a very significant factor, since it is expected, when high thermal conductivity nanometer-sized particles are added to a conventional heat transfer fluid, to reach for achieving higher value of thermal conductivity of the nanoparticle mixture. This property plays important role in the design and fabrication of energy-efficient heat transfer equipment. From the available literature, it was found that low thermal conductivity is a primary drawback in the growth of energy-efficient heat transfer fluids. Hence, nanoparticle suspended base fluids are needed to show high thermal conductivities compared to those of base heat transfer fluids for efficient utilization in heat transfer processes. These fluids are beneficial in

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Paper received: 4 May, 2020
Paper revised: 25 July, 2020
Paper accepted: 24 September, 2020

https://doi.org/10.2298/CICEQ200504036P

various industries such as transportation, chemical, electronics cooling, space, nuclear and food industries [1]. Corrugated heat exchangers are very useful in dairy industries because of their outstanding heat transfer coefficient characteristics and compact designs [2].

The following literature are studies based on the effect of thermophysical properties with respect to nanofluid: the initial idea was proposed by Choi *et al.* [3] for enhancing the thermal conductivity of base heat transfer fluids by adding and mixing nanoparticles in a base fluid. They observed that metals and metal oxides possess higher thermal conductivity than the base fluids. Sarafraz *et al.* [4] framed a research work for studying the pool boiling heat transfer behaviour of MEG/DEG/water ternary mixture suspended nanofluid and developed a new correlation. Rasher *et al.* [5] studied the viscosity effect on aluminium oxide suspended pure propylene glycol at a temperature range of 30 to 60 °C and a nanoparticle volume fraction of 0.5 to 3%; they varied the nanoparticle size (27, 40 and 50 nm). They reported incremental effect on viscosity of nanoparticle suspension. Kulkarni *et al.* [6] performed investigation on rheological properties with copper oxide nanoparticles suspended in a propylene glycol/water mixture. Their operating temperature ranged between -35 and 50 °C; they have also varied the particle volume fraction (0-5.9%). They made comparative analysis of experimental data with ASHRAE data (2005) and Bachelor's correlation equation (1977), and observed better agreement with ASHRAE data, whereas the Bachelor's correlation showed substantial deviation. The thermodynamic feasibility of the liquid chemical looping gasification (LCLG) in syngas production was made by Sarafraz *et al.* [7]. In this study, copper oxide is implemented as an oxygen carrier for chemical looping gasification process. The proposed system offers a potential benefit to avoid agglomeration and sintering, which implies that no further process is required in separation of the evaporated copper oxide from the syngas.

Aluminium oxide and copper oxide suspended water nanofluid was analysed by Nguyen *et al.* [8] for the effect of nanoparticle addition on viscosity of base fluids. They have conducted the study by varying the nanoparticle volume fraction, size of the nanoparticle and operating temperature. The obtained results revealed that viscosity is strongly influenced by the volume concentration of the nanoparticle. However, with respect to particle size the dependency of the viscosity is less significant. The experimental study was conducted by Namburu *et al.* [9] with SiO_2 nanoparticle suspended in a base fluid of water and ethylene glycol mixture. Their objective was to find the viscosity effect on the addition of SiO_2 nanoparticle with 20, 50 and 100 nm. They observed lowest viscosity 100-nm-sized SiO_2 nanoparticle at 8% volume fraction. Silver nanoparticle suspension in water was used by Godson *et al.* [10] to find the viscosity effect of silver nanoparticle dispersed in deionized water. Their operating conditions were experimental temperature of 50 to 90 °C and the nanoparticle volume concentration of 0.3-0.9%. The study demonstrates the effect of Brownian motion and thermophoresis on the thermophysical properties of base fluid. They also developed an experimental correlation for viscosity relating with the temperature and nanoparticle volume fraction. Sarafraz [11] prepared dispersions of CuO nanoparticles in water/ethylene glycol mixture at 50-50 volumetric concentrations, in order to study the sedimentation effects and convective boiling characteristics of the prepared fluid. Comparative analysis was made between the experimental results and correlations (Chen, Gun-gor-Winterson, Rohsenow) and the study recommends Chen correlation is suitable to determine the convective flow boiling heat transfer coefficient of prepared nanofluid. The study was conducted by Sarafraz *et al.* [12] with biologically produced silver/coconut oil nanofluid. The objective of the study was to quantify the thermal conductivity, viscosity and boiling heat transfer coefficient of biologically produced nanofluid. The assessment of thermal performance is also made with the prepared nanofluid in annular heat exchanger. Due to the enhancement in thermal conductivity and viscosity of the base fluid, the study reveals that this nanofluid can be used as a lubricant as well as a coolant in engines.

The density variation with ZnO, Sb_2O_5:SnO_2 and Al_2O_3 nanoparticles suspended in ethylene glycol//water mixture base fluid was studied by Vajjha *et al.* [13]. They measured the changes in density of nanoparticle suspended base fluid. They operated at the temperature range between 0 and 50 °C with 1-10 % volume fraction of nanoparticle suspension. Their experimental results were compared by Pak and Cho model and obtained better agreement with the measured values at all temperatures. They have noted 1.2% deviation for Al_2O_3 and Sb_2O_5:SnO_2 nanoparticles and 8% deviation for ZnO nanoparticle. The effect of ZnO nanoparticle suspension on density of water/ethylene glycol mixture base fluid was done by Mahian *et al.* [14]. They have prepared EG/water mixture of weight ratio 40-60, their temperature range between 25 and 40 °C and the ZnO volume fraction was 4.0%. They observed maximum density of 1328 kg/m^3 at a temperature of 25 °C for a 4.0% nanoparticle volume fraction.

The specific heat capacity of titanium oxide and aluminium oxide nanoparticles suspended in a base fluid mixture of water and ethylene glycol (20/80 wt.%) was measured by Yiamsawasd *et al.* [15]. They have determined specific heat based on a differential thermal analysis technique with a temperature between 15 and 65 °C and nanoparticle volume fraction of 8.0 vol.%. They framed new correlation to estimate the specific heat capacity of suspended nanoparticles in a form of specific heat ratio between nanofluid and base fluid. Satti *et al.* [16] prepared CuO, Al_2O_3, SiO_2, ZnO and TiO_2 nanoparticles diluted in water/propylene glycol (40:60 volume ratio) base fluid. They measured the variation in specific heat capacity with respect to the effects of nanoparticle volume fraction between 0.5 and 6 vol.%, operating temperature ranges between 243 and 363 K and particle sizes of 15 and 76 nm. The results revealed that the specific heat capacity decreases with increase in nanoparticle volume fraction and the specific heat capacity increases with increase in temperature, which were in good agreement with already published results.

The experiment was performed by Lee *et al.* [17] to study the thermal conductivity effect on Al_2O_3/ /ethylene glycol, Al_2O_3/water, CuO/water and CuO/ /ethylene glycol base fluids with vol.% from 1 to 5. They reported that only a small amount of nanoparticles have considerably high values of thermal conductivities than the base fluid without nanoparticles. The study conducted by Xuan and Li [18] by the suspension of copper nanoparticle, reported that the thermal conductivity of nanofluid is affected by the shape, size, volume fraction, and properties of the nanoparticle. Eastman *et al.* [19] studied the performance of copper nanoparticles directly suspended in ethylene glycol and reported significant enhancement in thermal conductivity of the base fluid containing smaller-sized copper nanoparticles. An experiment study was conducted by Das *et al.* [20] to determine the effects of temperature variation on thermal conductivity. They have used Al_2O_3/CuO nanoparticles suspended in water base fluid. By applying wavering method, they have calculated the thermal conductivity. They observed an increasing trend of thermal conductivity with an increase in temperature. Their finding also reveals that nanoparticle suspensions will be better at high temperature. Murshed *et al.* [21] studied the thermal conductivity effect of TiO_2 suspended deionized water and reported that nanoparticles in small quantity have much higher thermal conductivities than conventional fluid. Evans *et al.* [22] studied the variations of temperature and Al_2O_3 nanoparticle size and demonstrated the hydrodynamics effects associated with Brownian motion on the thermal conductivity of the nanoparticle suspended base fluid. Their finding shows that a nanoparticle is approximately 10 times more conductive than base fluid. Li and Peterson [23] investigated with copper oxide and aluminium oxide suspension in water with 2 to 10 vol.% of nanoparticle volume fraction and 27.5 to 34.7 °C of temperatures. A linear regression equation was proposed to determine the thermal conductivity ratio based on temperature and nanoparticle volume fraction. The experimental study was conducted by Vajjah and Das [24] for Al_2O_3, CuO and ZnO nanoparticle suspension in a base fluid of water and ethylene glycol. Their test conditions were 10% of nano particle volume fraction and 298 to 363 K temperature range. Their study reveals there is an increase in thermal conductivity of nanofluid with respect to nanoparticle volume fraction and temperature, and 18% thermal conductivity ratio enhancement was observed for ZnO suspension at the 7% volume fraction of nanoparticle. Xie *et al.* [25] studied with ethylene glycol (EG) suspended with TiO_2, MgO, ZnO, Al_2O_3 and SiO_2 nanoparticles and reported that the MgO/EG suspension has the highest thermal conductivity and the lowest viscosity. They concluded that at 30 °C the thermal conductivity enhancement was 40.6% for a 5% volume concentration for MgO nanoparticle. The thermal conductivity study with titanium dioxide and aluminium oxide nanoparticle suspended in propylene glycol base fluid was made by Palabiyik *et al.* [26]. Their observation was different to the many literature results, since they have reported results of nonlinear behaviour with the selected nanoparticle volume fraction. They also reported that with respect to temperature, the enhancement in thermal conductivity was not varying significantly. The rheological behavior and heat transfer performance of various metal-based nanofluids (silver, copper, alumina, TiO_2) were studied by Pourmehran *et al.* [27] and reported that the Brownian motion is considered to simulate viscosity of nanofluid. They have used the Patel model to predict the thermal conductivity. According to their results it was observed that maximum value of heat transfer enhancement is obtained by selecting the silver (Ag) as nanoparticle.

Silicon dioxide and EG/water were used by Sahoo *et al.* [28] to investigate the impact of nanoparticle suspension in EG/water base fluid on the thermal conductivity. They observed 20% enhancement in a base fluid thermal conductivity. Their process conditions were 20 to 90 °C temperature and a nanoparticle concentration of 10 vol.%.

The thermal conductivity behaviour of deionized water and ethylene glycol after ing graphene and graphene multi-walled carbon nano-tubes (MWCNTs) was studied by Aravind and Ramaprabhu [29]. They reported that 9.2 and 73% improvement in deionized water for nanoparticle concentration of 0.04% at temperature of 25 and 50 °C, respectively. The enhancement was 6.9 and 20% for ethylene glycol base fluid at the same nanoparticle volume fraction and temperature, respectively. They concluded that the increase in nanoparticle volume fraction increases thermal conductivity of nanofluid. Manikandan *et al.* [30] performed heat transfer studies in a corrugated plate heat exchanger with TiO_2 and ZnO diluted in a base fluid mixture of water and ethylene glycol and reported there is a significant improvement in the heat transfer rate by the nanoparticle suspension. The experimental study performed by Sundar *et al.* [31] with the prepared magnetic Fe_3O_4 nanoparticle dispersed in water, showed 8.4 and 17% enhancement in thermal conductivity at temperatures of 20 and 60 °C, respectively. They have prepared 0 to 2% volume fraction of nanoparticle suspension. Barbés *et al.* [32] measured the thermal conductivity and specific heat capacity for aluminium oxide suspended in water as well as ethylene glycol base fluid. Their study conditions were 298 to 338 K temperatures and a nanoparticle volume fraction of 1.0-10.0%. Their results reveal that thermal conductivity of suspension increased but the specific heat capacity of suspension decreased with respect to nanoparticle concentration. Graphene suspended water base fluid was prepared by Ahammed *et al.* [33] to study the thermal conductivity variation of a nanoparticle addition. Their concentrations of nanoparticle were 0.05, 0.1 and 0.15 vol.% and temperatures were in the range of 10--50 °C. They have noted that the thermal conductivity ratio was improved by 6.7 and 18.6% at 10 and 50 °C, respectively, for a nanoparticle volume fraction of 0.05%. The result confirmed that the thermal conductivity of graphene based nanofluid has a considerable impact against process temperature. It was also noted from the study that 3.3% higher thermal conductivity enhancement occurred with the increase in volume concentration. Graphene and copper suspended ethylene glycol/water base fluid used by Periasamy *et al.* [34,35] observed that the nanoparticle volume fraction has the significant effect on thermal conductivity of base fluids. A new correlation was proposed by Sarafraz [36] for the determination of the Nusselt number based on the investigation of the thermal performance and pressure drop characteristics of liquid indium mixed with copper oxide nanoparticles in a rectangular micro-channel.

Different metal oxide nanoparticles (CuO, Al_2O_3, SiO_2 and ZnO) were suspended by Satti *et al.* [37] in a propylene glycol and water mixture. They determined the thermal conductivity at a 6% volumetric fraction of nanoparticles and 30 to 90 °C temperature range. They observed an increase in thermal conductivity of nanoparticle suspension with increasing nanoparticle volume fraction and fluid temperature. The effect of ethanol/MEG/DEG ternary mixture suspension on nucleate pool boiling heat transfer characteristics were studied by Sarafraz *et al.* [38] and observed significant changes in thermophysical properties. They summarized the factors affecting the thermal conductivity of nanoparticle suspensions which are properties of particles and the base fluid, nanoparticle volumetric concentration, particle size and temperature. This result is helpful because the thermal conductivity improved working fluids may be utilized at higher temperature applications. The potential application of a liquid metal enriched with Al_2O_3 nanoparticle was studied by Sarafraz *et al.* [39] in a micro-channel solar thermal receiver with 5, 10 and 15% (mass fractions). They investigated thermal performance of the suspended nanoparticle and achieved the highest thermal performance index of 3.5 and 2.9 for the laminar and turbulent flow, respectively, at mass fraction of 10%. In order to study the heat transfer coefficient, thermal resistance and the thermal performance of a thermosyphon heat pipe, zirconia-acetone nanofluid was prepared by Sarafraz *et al.* [40]. Results showed that the presence of the nanofluid decreases the total thermal resistance and enhanced the boiling heat transfer mechanism, which resulted in the thermal performance enhancement of the heat pipe. To assess the thermal performance, a new correlation was proposed from the study to predict the Kutateladze number. Sarafraz *et al.* [41] made an experimental investigation on the thermal performance and efficiency of an evacuated tube solar collector (ETSC) with graphene-methanol nanofluid. It was revealed from the study that the presence of nanoparticles improved the thermal conductivity of methanol, while the heat capacity of the nanofluid decreased by a decrease in the mass fraction of the graphene. The different concentrations of Fe_3O_4 nanoparticles in water were used by Sarafraz *et al.* [42] to quantify the heat transfer coefficient of nanofluid under constant magnetic field. Results showed that the magnetic field can lower the fouling resistance providing that the nanosuspension is stable. Hence the heat transfer coefficient value was also improved with the Fe_3O_4 nanosuspensions.

Some of the significant studies with respect to graphene nanoparticles are given in the following section; graphene oxide/water nanofluid was synthesized by Liu *et al.* [43] using modified Hummers' method. They have investigated the stability of the prepared nanofluids using UV spectroscopy and showed that nanofluid stability is >3 months and also that 1.0 mg/ml nanofluid can work in applications with an operational range up to 1000 °C. The study provides new correlation to calculate thermal conductivity of nanofluids. It is revealed from the study that graphene oxide nanoparticles synthesized by modified Hummers' method, can be used as a stable nanofluid with acceptable heat transfer potential in thermal systems. Heat transfer studies in a three-dimensional spiral heat exchanger were performed by Bahiraei *et al.* [44]. In this study, thermal and hydraulic attributes of a graphene nanofluid in a countercurrent spiral heat exchanger were evaluated. They determined the performance index (ratio of heat transfer rate to pressure drop) and reports that performance index enhances with increase in either nanoparticle concentration or Reynolds number. Bahiraei *et al.* [45] made an investigation on thermo-hydraulic performance of graphene nanoplatelets. They performed the test within a tube enhanced with rotating twisted tape. The results revealed that the convective heat transfer coefficient and pumping power increase by increasing the rotational speed and weight fraction, while they decrease by increasing the twisted ratio. The effect of nitrogen-doped graphene (NDG) nanofluids concentration on heat transfer and fluid flow in double-pipe heat exchangers was made by Marjan Goodarzi *et al.* [46]. A novel MATLAB code solved the governing equations were used to analyze the resulting heat transfer coefficient, pressure drop, wall temperature reduction and pumping power. Khan *et al.* [47] investigated a blend of *Nigella sativa* biodiesel, diesel, n-butanol, and graphene oxide nanoparticles to enhance the performance, combustion and symmetric characteristics and to reduce the emissions from the diesel engine of a modified common rail direct injection (CRDI). The results obtained indicate that 90 ppm of graphene oxide nanoparticles and 10% *n*-butanol in *Nigella sativa* biodiesel are comparable with diesel fuel. Safaei *et al.* [48,49] used graphene oxide nanofluids in solar-driven water desalination process and developed an empirical equation to correlate the average Nusselt number as a function of Rayleigh number (Ra), the Stefan number (Ste), the sub-cooling factor (Sb), and the Fourier number (Fo). Sarafraz *et al.* [50] conducted an experimental investigation on heat transfer performance of graphene nanoplatelets/pentane nanofluid in a gravity-assisted heat pipe. They observed enhancement in heat transfer coefficient by increasing the heat flux. Experimental heat transfer studies were conducted by Sarafraz *et al.* [51] by using graphene nano-platelets dispersed in water-ethylene glycol mixture and reported that the thermal performance of the system increased by 21% in terms of heat transfer coefficient. The new preparation method for the decoration of platinum (Pt) on the functionalized graphene nanoplatelet (GNP) was introduced by Yarmand *et al.* [52]. Based on the stability analysis, it was noticed that nanofluids were stable and no significant sedimentation was observed for a long time (22 days).

According to the published articles, extensive research was conducted only on thermal conductivity measurement of nanofluids. The influence of other thermophysical properties such as viscosity, density and specific heat capacity variations were not studied much with added nanoparticles. Since these thermophysical properties may improve the heat transfer performance of the conventional base fluids, and also improve the application of nanofluid in heat exchangers, a complete understanding of the thermophysical properties is necessary. Also, from the published literature, it was identified that ethylene glycol is a viable heat transfer fluid because of its thermal characteristics, but it was noticed that only limited studies were performed with ethylene glycol as a base fluid.

Graphene is one of the most studied carbon-based nanofluids because of its larger surface/volume ratio, higher thermal conductivity, lower erosion, corrosion and clogging. It was found from the literature that mostly thermal conductivity studies were performed with graphene nanofluid. Since there will be a scope for exploring other thermophysical properties (viscosity, density and specific heat capacity) of graphene nanoparticle, this study was chosen. The novelty of the present study is considering graphene as a nanoparticle and performing the thermophysical characteristics analysis of the graphene suspended ethylene glycol/water mixture.

MATERIALS AND METHODS

Experimental setup

In order to study the thermophysical characteristics of graphene nanoparticle suspended EG/water base fluid, the experimental setup consists of a hot and cold fluid tank (20 L), four thermocouples, two pumps, two flow meters, and a corrugated plate heat exchanger (PHE) was fabricated and the outline and photograph of the experimental setup is shown in Figures 1 and 2, respectively.

Figure 2. Photograph of experimental setup.

Experimental procedure

The water is pumped from the hot fluid tank and its temperature is constantly maintained at approximately 55 °C using a thermostat and the outlet is returned to the outlet tank.

Hummers' method was employed for producing graphene nanoparticles.

The prepared nanoparticle suspension (graphene/EG/water) in the cold fluid tank is also pumped into the plate heat exchanger.

The inlet and outlet temperatures of cold and hot fluid were measured using the inserted thermocouples.

A rotameter was used to measure and control the flow rates.

Experiments were repeated by varying the hot fluid temperatures to 65 and 75 °C and the nanoparticle suspension volume fractions of 0.2, 0.4, 0.6, 0.8 and 1%.

In order to compare the results, experiments with base fluid (EG/water) used as cold fluid were carried out first and the results were compared with the graphene suspended base fluid.

Nanofluid preparation and characterization

Graphene nanoparticles were produced by the Hummers' method [53]. The prepared nanoparticles were dispersed in the base fluid (ethylene glycol/ /water mixture) as per the proposed ratio and the nanofluids were used in our study. Figure 3 provides the TEM image of graphene nanofluids at 1.0 volume fraction.

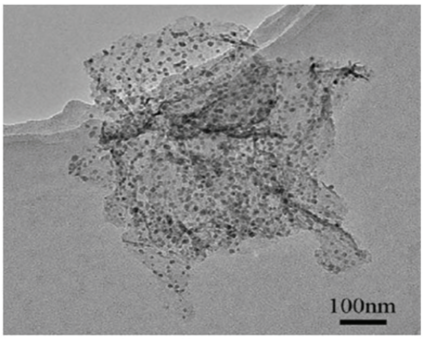

Figure 3. TEM image of graphene nanofluids at 1.0 volume fraction.

Calculation of thermophysical properties

In order to calculate thermo physical properties such as viscosity, density, specific heat capacity and

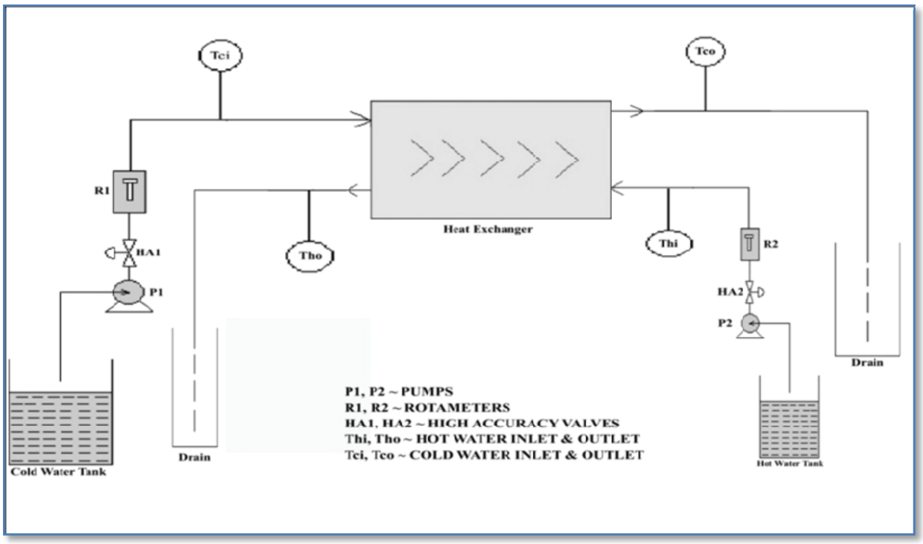

Figure 1. Outline of experimental setup.

thermal conductivity of nanoparticle suspension, the following thermophysical property models were used in the present study.

(i) Viscosity models

1. Einstein model

$$\mu_{nano} = (1+2.5\varphi)\,\mu_{base}$$

2. Kitano model

$$\mu_{nano} = \left[\left(1-\frac{\varphi}{\varphi m}\right)\right]\mu_{base}$$

3. Bachelor model

$$\mu_{nano} = (1+2.5\varphi+6.2\varphi_2)\,\mu_{base}$$

(ii) Density model

1. Pak and Cho model

$$\rho_{nano} = (1-\varphi)\,\rho_{base} + \varphi\rho_{base}$$

(iii) Specific heat capacity model

1. Xuan model

$$Cp_{nano} = \frac{\left((1-\varphi)\rho_{base}Cp_{base} + \varphi_{base}\rho_{nano}Cp_{nano})\right)}{((1-\varphi)\rho_{base} + \varphi\rho_{nano}}$$

2. Pak and Cho model

$$Cp_{nano} = (1-\varphi)\,Cp_{base} + \varphi Cp_{particle}$$

(iv) Thermal conductivity models

1. Maxwell model

$$\frac{K_{fluid}}{K_{base}} = \frac{K_{particle} + 2K_{base} + 2\varphi(K_{particle} - K_{base})}{K_{particle} + 2_{Kbase} - \varphi(K_{particle} - K_{base})}$$

2. Vajjha Model

$$\frac{K_{fluid}}{K_{base}} = (0.0282\varphi + 0.0039)\left(\frac{T}{T_0}\right) +$$
$$+(-0.0307\varphi - 0.0039)$$

3. Sahoo Model

$$\frac{K_{fluid}}{K_{base}} = (-0.4557)\left(\frac{T}{T_0}\right)^2 + 1.72837(\frac{T}{T_0}) - 0.18559$$

RESULTS AND DISCUSSION

Impact of graphene nanoparticle concentration on viscosity of base fluid suspension

Viscosity indicates the resistance offered by the fluid. To consider the effect on viscosity, Einstein (1956), Kitano (1981) and Bachelor (1977) models have been taken to compare experimental results.

Figure 4a shows the influence of graphene nanoparticle suspension on the viscosity of base fluid at a hot fluid inlet temperature of 55 °C and base fluid concentrations of 30:70 (EG:W). From the figure, it was observed that the viscosity increases with the increase in graphene nanoparticle concentration. This is due to the fact that viscosity is strongly influenced by the volume concentration of the nanoparticle. Figure 4b presents the effect of nanoparticle addition on viscosity of base fluid at a hot fluid inlet temperature of 65 °C. At this temperature, an increase in nanoparticle volume fraction increased the viscosity in all the selected models with approximately equal values. It was also observed that the magnitude of viscosity decreases with increase in hot fluid inlet temperature. Figure 4c provides the plot for the influence of nanoparticle concentration on viscosity of base fluid suspension at the hot fluid inlet temperature of 75 °C. It was observed that at a hot fluid inlet temperature of 75 °C, an increase in nanoparticle concentration increased the viscosity of base fluid at the prepared base fluid concentration. This behaviour is attributed to the fact that the increase in nanoparticle concentration increases the viscosity of base fluids but the increase

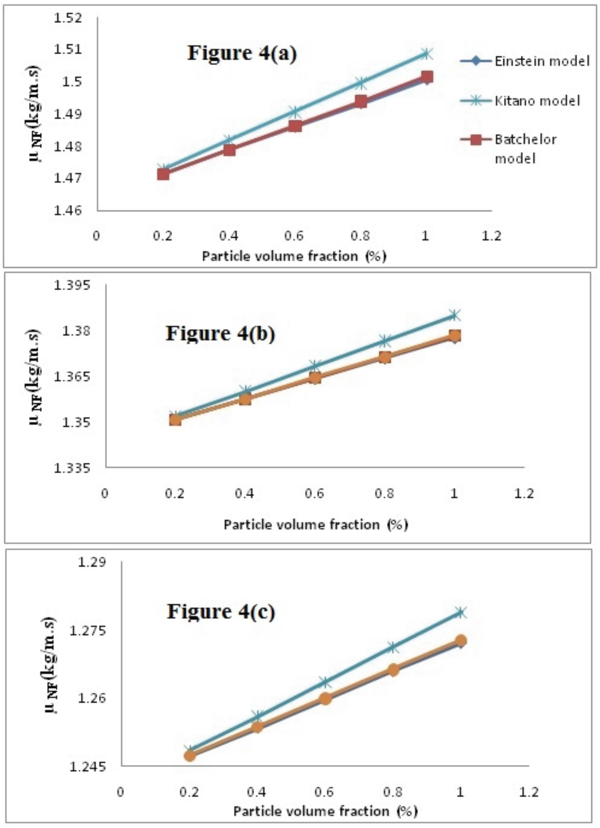

Figure 4. The influence of graphene nanoparticle concentration on viscosity of a base fluid concentration of 30:70 (EG:W) at a hot fluid inlet temperature of: a) 55, b) 65 and c) 75 °C.

in hot fluid inlet temperature decreases the viscosity of nanoparticle suspended base fluids.

Impact of graphene nanoparticle concentration on density of nanofluid

The density of metal oxides is greater than that of liquids. Density and specific heat capacity are determined as a function of particle volume fraction on the principle of two-phase mixtures. Density is considered an important parameter for evaluating the heat transfer performance of nanofluid. Figure 5a-c presents the effect of graphene nanoparticle addition on the density of nanofluid for the base fluid concentrations of 30:70 (EG:W) at the hot fluid inlet temperature of 55, 65 and 75 °C, respectively. The measured density data was validated with the Pak and Cho model.

The addition of graphene nanoparticle increased the density of the base fluid mixture. The reason for this is the nanofluid density is higher than that of the base fluid. It was noticed that the density of base fluid increased gradually with respect to the entire particle volume fraction, but the density decreases with respect to all the three hot fluid temperatures. The maximum density was observed at 1.0 vol.% for all the base fluid concentrations. The maximum density observed in the Pak and Cho model is 1037 kg/m^3 for 30:70 (EG:W). The result shows that nanofluid density increases with increase in nanoparticle concentration and decreases with increase in hot fluid inlet temperature.

Effect of graphene nanoparticle concentration on specific heat capacity of nanofluid

Specific heat is the amount of heat required to raise the temperature of one gram of nanofluid by one degree centigrade. Specific heat is one of the important properties and plays an important role in influencing the heat transfer rate of nanofluid. Figure 6a-c presents the effects of graphene nanoparticle volume fraction on specific heat capacity of nanoparticle suspension at a hot fluid inlet temperature of 55 °C and base fluid concentrations of 30:70 (EG:W) at a hot fluid inlet temperatures of 55, 65 and 75 °C, respectively.

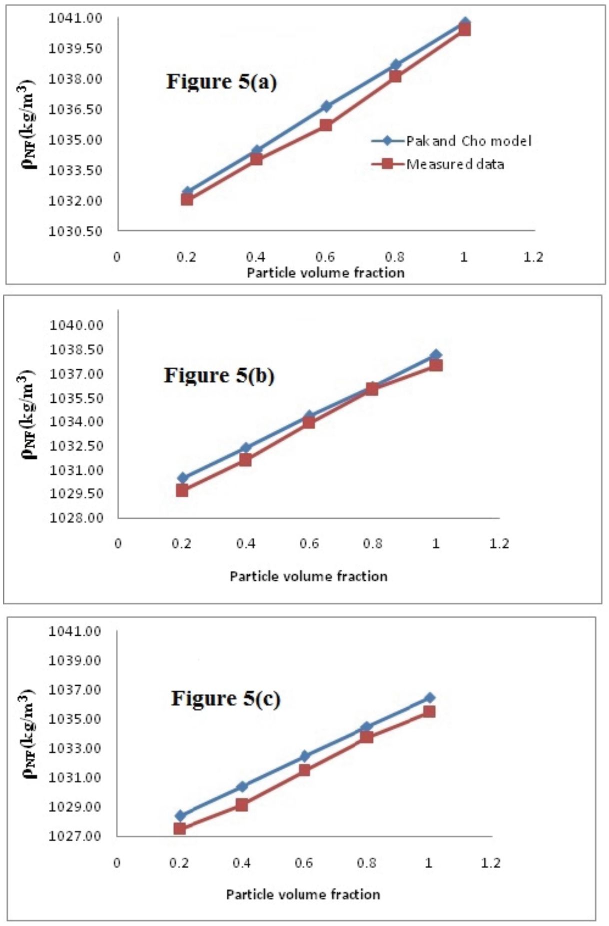

Figure 5. The influence of graphene nanoparticle concentration on density of a base fluid concentration of 30:70 (EG:W) and a hot fluid inlet temperature of: a) 55, b) 65 and c) 75 °C.

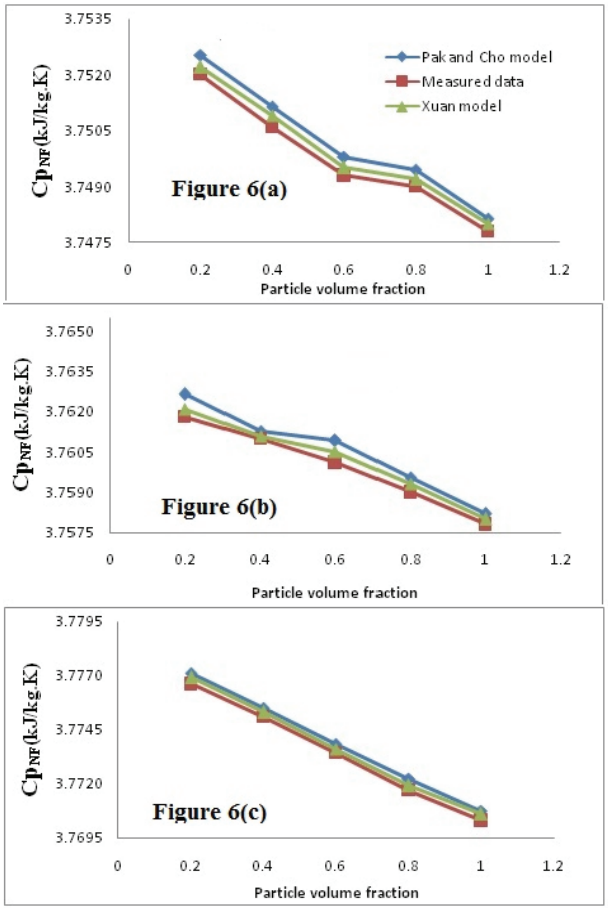

Figure 6. The influence of graphene nanoparticle concentration on specific heat capacity of base fluid concentration of 30:70 (EG:W) at a hot fluid inlet temperature of: a) 55, b) 65 and c) 75 °C.

Increase in nanoparticle concentration leads to decrease in specific heat capacity. It can be observed from the results that the values of specific heat capacity decreased from 3.762 to 3.7582 kJ/(kg K) with increase in volume concentration between 0.2 and 1.0% as per the Pak and Cho model for a base fluid concentration of 30:70 (EG:W) and a temperature of 65 °C. The reason for this is due to the fact that specific heat capacity is a mass specific quantity and this effect depends on the density of components and its mixture. The effect of graphene nanoparticle addition on specific heat capacity of nanofluid at a hot fluid inlet temperature of 75 °C and a base fluid concentration of 30 vol.% of ethylene glycol base fluids is shown in Figure 5c. The nanoparticle specific heat capacity decreased with increase in nanoparticle concentration for all the three base fluid concentrations. No significant variations were observed in specific heat capacity of nanofluid with respect to temperature. The experimental result was validated with Pak and Cho, and Xuan models. A better agreement was obtained between the measured values with selected models at all base fluid concentrations.

Effect of graphene nanoparticle concentration on thermal conductivity ratio of nanofluid

Thermal conductivity ratio (K_{nf}/K_{bf}) is an important parameter in measuring the effectiveness of the nanoparticle addition in the base fluid. For this purpose, comparisons between thermal conductivity ratio values of graphene nanoparticle with respect to base fluid concentration (30:70 (EG:W)) and at a hot fluid inlet temperatures of 55, 65 and 75 °C were plotted in Figure 6a-c, respectively. To consider the effect of Thermal conductivity ratio, three different models (Maxwell model (1954), Vajjah model (2010), and Sahoo model (2012)) have been used to compare experimental results with base fluids.

Figure 7a depicts the effects of nanoparticle addition on thermal conductivity ratio of the nanofluid at a hot fluid inlet temperature of 55 °C. The thermal conductivity ratio increased gradually at all the nanofluid concentrations due to the fact that nanoparticle volume fraction is directly proportional to thermal conductivity. At the variation of hot fluid inlet temperature at 65 °C (Figure 7b, the thermal conductivity increases with increase in volume fraction of nanoparticle in the base fluid concentration of 30:70 (EG:W). The improvement is higher than at the hot fluid temperature of 55 °C, due to the temperature effect (if temperature increases then thermal conductivity also increases). Further increase of hot fluid inlet temperature at 75 °C (Figure 7c) shows significant increases in thermal conductivity ratio. This is due to the fact that thermal conductivity is significantly affected by temperature and nanoparticle volume fraction, because of the expanded surface area of the dispersed nanoparticle in base fluid. The thermal conductivity predictions based on the selected published models were compared. Thermal conductivity increased gradually in all the selected models, which is due to the addition of nanoparticle to the base fluid. From the comparison of the thermal conductivity with the standard correlations (Maxwell model (1954), Vajjah model (2010) and Sahoo model (2012)) it is evident that increase in volume fraction of nanoparticle improved the thermal conductivity due to random Brownian motion, particle morphology, inter-particulate diffusion effects, and possible decrease in the boundary layer thickness.

There exists good agreement between the results calculated from experimental and different models. It was noticed that the density and specific heat capacity variations fall within ±5% deviation with experimental results and ±8 % deviation for viscosity and thermal conductivity variations. Hence, there exists good agreement between the correlation

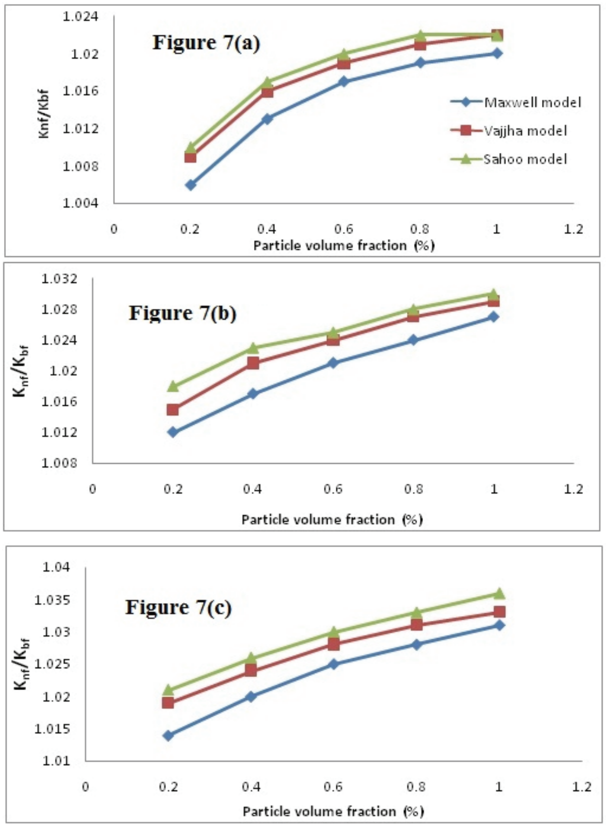

Figure 7. The influence of graphene nanoparticle concentration on thermal conductivity ratio of a base fluid concentration of 30:70 (EG:W) and a hot fluid inlet temperature of: a) 55, b) 65 and c) 75 °C.

results and experimental results, which shows the accuracy of the results of the experiment.

CONCLUSION

The study revealed that the hot fluid inlet temperature and nanofluid concentration have significant effects on the thermophysical properties of graphene suspended base fluids. There is an increase in viscosity from 1.247 to 1.272 kg/(m s) with respect to 75 °C of inlet temperature. At 55 °C, the base fluid has a higher density of 1041 kg/m^3 at 1.0 vol.%, however, the density of the mixture has the lowest value of 1028 kg/m^3 at 75 °C. Hence, the density increases with nanoparticle concentration and decreases with hot fluid inlet temperature. The dispersed nanoparticle shows lower specific heat than the values of base liquid. The observed specific heat capacity at 55 °C is 3.752 kJ/(kg K) (at 0.2 vol.%) which is reduced to 3.747 kJ/(kg K) (1.0 vol.%). Hence, the specific heat of nanofluid decreases with the increase in nanoparticle concentration, and the specific heat of nanofluid does not vary significantly with hot fluid inlet temperature. The obtained thermal conductivity ratios of base fluid are maximum at 75 °C and 1.0 vol.% with a value of 1.031, which is higher than those of base fluid. For all the thermophysical properties, the selected correlation models showed good agreement with the experimental results.

Acknowledgment

The authors thank the management of Kongu Engineering College and Department of Chemical Engineering for the facility provided.

Nomenclature

Vol.%	Volume %
EG	Ethylene glycol
W	Water
C_p	Specific heat capacity, J/(kg.K)

Greek symbols

k	Thermal conductivity, W/(m.K)
μ	Viscosity, kg/m.s
ρ	Density, kg/m3
φ	Particle volume fraction

Subscripts

nano	Nanofluid
base	Base fluid

REFERENCES

[1] M. Sabiha, R. Saidur, S. Mekhilef, O. Mahian, Renewable Sustainable Energy Rev.51 (2015) 1038-1054

[2] S. Sarafraz, M. Peyghambarzadeh, N. Vaeli, Chem. Ind. Chem. Eng. Q. 18 (2012) 315-327

[3] S.U.S. Choi, S. Lee, S. Li, J.A. Eastman, J. Heat Transfer 121 (1999) 280-289

[4] M. Sarafraz, A.S. Fazel, Y. Hasanzadeh, A. Arabshamsabadi, S. Bahram, Chem. Ind. Chem. Eng. Q. 18 (2012) 11-18

[5] R. Prasher, D. Song, J. Wang, P. Phelan, Appl. Phys. Lett. 89 (2006) 133108

[6] D.P. Kulkarni, D.K. Das, S.L. Patil, J. Nanosci. Nanotechnol. 7 (2007) 2318-2322

[7] M.M. Sarafraz, M. Jafarian, M. Arjomandi, G.J. Nathan, Appl. Energy 195(2017) 702-712

[8] C.T. Nguyen, F. Desgranges, G. Roy, N. Galanis, T. Maré, S. Boucher, Int. J. Heat Fluid Flow 28 (2007) 1492--1506

[9] P. Namburu, D. Kulkarni, A. Dandekar, D. Das, Micro Nano Lett. 2 (2007) 67-71

[10] L. Godson, B. Raja, D.M. Lal, S. Wongwises, Exp. Heat Transfer 23 (2010) 317-332

[11] M.M. Sarafraz, F. Hormozi, M. Kamalgharibi, Heat Mass Transf. 50(2014) 1237-1249

[12] M.M. Sarafraz, Chem. Biochem. Eng. Q. 30 (2017) 489--500

[13] R.S. Vajjha, D.K. Das, B.M. Mahagaonkar, Pet. Sci. Technol. 27 (2009) 612-624

[14] O. Mahian, A. Kianifar, S.A. Kalogirou, I. Pop, S. Wongwises, Int. J. Heat Mass Transfer 57 (2013) 582-594

[15] T. Yiamsawasd, A.S. Dalkilic, S. Wongwises, Curr. Nanosci. 8 (2012) 939-944

[16] J.R. Satti, D.K. Das, D. Ray, Int. J. Heat Mass Transfer 94 (2016) 343-353

[17] G.J. Lee, C.K. Kim, M.K. Lee, C.K. Rhee, S. Kim, C. Kim, Thermochim. Acta. 542 (2012) 24-27

[18] Y. Xuan, Q. Li, J. Heat Transfer 125 (2003) 151-155

[19] J.A. Eastman, S.U.S Choi, S. Li, W. Yu, L.J. Thompson, Appl. Phys. Lett. 78 (2001) 718-720

[20] S.K. Das, N. Putra, P. Thiesen, W. Roetzel, J. Heat Transfer 125 (2003) 567-574

[21] S.M.S. Murshed, Heat Transfer Eng. 33 (2012) 722-731

[22] W. Evans, J. Fish, P. Keblinsk, Appl. Phys. Lett. 88 (2006) 093116

[23] C.H. Li, G. Peterson J. Appl. Phys. 99 (2006) 084314

[24] R.S. Vajjha, D.K. Das, Int. J. Heat Mass Transfer 52 (2009) 4675-4682

[25] H. Xie, J. Wang, T. Xi, Y. Liu, Int. J. Thermophys. 23 (2002) 571-580

[26] I. Palabiyik, Z. Musina, S. Witharana, Y. Ding, J. Nanopart. Res. 13 (2011) 5049-5055

[27] O. Pourmehran, M. M. Sarafraz, M. Rahimi-Gojiri, D. D. Ganji, J. Taiwan Inst. Chem. Eng., 2018, Article in press

[28] B.C. Sahoo, D.K. Das, R.S. Vajjha, J.R. Satti, J. Nanotechnol. Eng. Med. 3 (2012) 041006

[29] S.S.J. Aravind, S. Ramaprabh. RSC Adv. 3 (2013) 4199--4206

[30] S.P. Manikandan, R. Baskar, Chem. Ind. Chem. Eng. Q. 24 (2018) 309-318

[31] L.S. Sundar, M.K. Singh, A.C.M Sousa, Int. Commun. Mass Transfer 49 (2013) 17-24

[32] B. Barbés, R. Páramo, E. Blanco, M.J. Pastoriza-Gallego, M.M. Piñeiro, J.L. Legido, J. Therm. Anal. Calorim. 111 (2013) 1615-1625

[33] N. Ahmed, L.G. Asirvatham, J. Titus, J.R. Bose, S. Wongwises, Int. Commun. Heat Mass Transfer 70 (2016) 66-74

[34] S.P. Manikandan, R. Baskar, Period. Polytech., Chem. Eng. 62 (2018) 317-322

[35] S.P. Manikandan, R. Baskar, Chem. Ind. Chem. Eng. Q. 27 (2021) 15-20

[36] M. M. Sarafraz, M. Arjomandi, Appl. Therm. Eng. 137 (2018) 700-709

[37] J.R. Satti, D.K. Das, D. Ray, Int. J. Heat Mass Trans. 107 (2017) 871-881

[38] M.M. Sarafraz, S. Peyghambarzadeh, F.S. Alavi, Chem. Ind. Chem. Eng. Q. 18 (2012) 577-586

[39] M.M. Sarafraz, M. Arjomandi, Int. Commun. Mass Transfer 94 (2018) 39-46

[40] M.M. Sarafraz, O. Pourmehran, B. Yang, M. Arjomandi, Renew. Energy 136(2019) 884-895

[41] M. Sarafraz, M.R. Safaei, Renew. Energy 142(2019) 364--372

[42] M.M. Sarafraz, O. Pourmehran, B. Yang, M. Arjomandi, R. Ellahi, Int. J. Therm. Sci. 147(2020) 106131

[43] W.I. Liu, O. Malekahmadi, S.A. Bagherzadeh, M. Ghashang, A. Karimipour, S. Hasani, T. Iskander, M. Goodarzi, Int. Commun. Mass Transfer 109(2019) 104333

[44] M. Bahiraei, H. Kiani Salmi, M.R. Safaei, Energy Convers. Manage. 180(2018) 72-82

[45] M. Bahiraei, N. Mazaheri, F. Aliee, M.R. Safaei, Powder Technol. 355(2019) 278-288

[46] M. Goodarzi, A.S. Kherbeet, M Afrand, E. Sadeghinezhad, M. Mahrali, P. Zahedi, S. Wongwises, M. Dahari, Int. Commun. Mass Transfer 76(2016) 16-23

[47] H. Khan, M.E.M. Soudagar, R.H. Kumar, M.R. Safaei, M. Farooq, A. Khidmatgar, N.R. Banapurmath, R.A. Farade, M.M. Abbas, A. Afsal, W. Ahmed, M. Goodarzi, S.N. Taqui, Symmetry 12(2020) 961

[48] M.R. Safaei, M. Safdari Shadloo, M.S. Goodarzi, A. Hadjadj, H.R. Goshayeshi, M. Afrand, S.N. Kazi, Adv. Mech. Eng. (London, U. K.) 8 (2016) 1-14

[49] M.R. Safaei, H.R. Goshayeshi, I. Chaer, Energies (Basel, Switz.) 12 (2019) 1-13

[50] M.M. Sarafraz, M.R. Safaei, Z. Tian, M. Goodarzi, E.P. Bandarra Filho, M. Arjomandi, Energies (Basel, Switz.) 12 (2019) 1-17

[51] M.M. Sarafraz, I. Tlili, Z. Tian, M. Bakouri, M.R. Safaei, M.S. Goodarzi, Appl. Sci. 9 (2019) 1-11

[52] H. Yarmand, S. Gharehkhani, S.F. Seyed Shirazi, M. Goodarzi, A. Amiri, W.S. Sarsama, M.S. Alehashem, M. Dahari, S.N. Kazi, Int. Commun. Heat Mass Transfer 77 (2016) 15-21

[53] W.S. Hummers, R.E. Offeman, J. Amer. Chem. Soc. 80 (1958) 1339.

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NAUČNI RAD

PROUČAVANJE PROMENA TERMOFIZIČKIH SVOJSTAVA NANOČESTICA GRAFENA SUSPENDOVANIH U SMEŠI ETILEN-GLIKOLA I VODE

Cilj ovog rada je bio da se utvrde promene termofizičkih svojstava (kao što su viskoznost, gustina, specifični toplotni kapacitet i toplotna provodljivost) bazne tečnosti (etilen-glikol/voda, EG/V) sa koncentracijom nanočestica grafena i ulaznom temperaturom vruće tečnosti. Korišćene koncentracije nanočestica grafena su 0,2, 0,4, 0,6, 0,8 i 1 vol.%, a bazna tečnost je sa 30 vol.% EG. Istraživan je uticaj dodavanja nanočestica grafena baznoj tečnosti u komercijalnom pločastom razmenjivaču toplote. U ovom eksperimentu temperatura ulaska vruće tečnosti bila je na 55, 65 i 75 °C. Eksperimentalni rezultati termofizičkih svojstava upoređeni su sa odabranim modelima predloženim u literaturi. Modeli Ajnštajna, Kitanoa i Bačelora korišćeni su za razmatranje uticaja na viskozitet. Izmerene vrednosti gustine, odnosno specifičnog toplotnog kapaciteta potvrđeni su modelima Paka i Ćua, odnosno Ksuana. Za toplotnu provodljivost korišćena su tri različita modela. Istraživanja su otkrila da se termofizička svojstva bazne tečnosti značajno menjaju dodtakom nanočestica grafena.

Ključne reči: grafen, nanočestice, termofizička svojstva, etilen-glikol, voda.