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The effect of particle size and base liquid on thermo-physical properties of ethylene and diethylene glycol based copper micro- and nanofluids

Nader Nikkam[a,*], Morteza Ghanbarpour[c], Rahmatollah Khodabandeh[c], Muhammet S. Toprak[b]

[a] Faculty of Life Sciences and Biotechnology, Shahid Beheshti University, Tehran 19839, Iran
[b] Department of Applied Physics, KTH Royal Institute of Technology, SE-10691 Stockholm, Sweden
[c] Department of Energy Technology, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden

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ABSTRACT

Nanofluid (NF) is a fluid containing nanometer-sized particles. The present work investigates, experimentally and theoretically, on fabrication and thermo-physical properties evaluation of ethylene glycol and diethylene glycol (EG/DEG) based nanofluids/microfluids (NFs/MFs) containing copper nanoparticles/microparticles (NPs/MPs) with focus on the effect of the particle size and the base liquid. A series of stable Cu NFs and MFs with various NP/MP concentration (1, 2 and 3 wt%) were fabricated by dispersing Cu NPs and Cu MPs in EG and DEG as the base liquids. The physicochemical properties of Cu NFs and MFs were analyzed by various techniques including X-Ray diffraction (XRD), Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM) and Dynamic Light Scattering (DLS). The thermo-physical properties including thermal conductivity (TC) and viscosity of EG/DEG based Cu NFs/MFs were measured at 20 to 40 °C. The results for TC and viscosity of EG based Cu NF/MFs were compared to the same NFs/MFs with DEG base liquid with focus on the impact of the particle size as well as the base liquid. The experiments showed that EG based NFs/MFs exhibit more favorable characteristics than that of DEG based ones. Moreover, NFs with Cu NPs revealed higher TC than those MFs containing Cu MPs at the same particle concentration and temperature (effect of NP size). As the best result, a TC enhancement of ~4.7% was achieved for EG based NF with 3 wt% Cu NP while maximum increase in viscosity of ~1.8% was observed for the same NF at 20 °C. To compare the experimental results with the estimated values, Maxwell predictive correlation and Corcione model were employed while Einstein equations as well as Kriger-Dougherty correlation were applied for TC and viscosity of NFs/MFs, respectively.

1. Introduction

The necessity for transport of heat using an appropriate fluid is quite common in industries including engineering devices, machine and plants producing energy. Heat transfer through a fluid typically takes place by convection which can be enhanced by some factors such as improved thermal conductivity of the fluid. It is well known that the suspension containing solid particles may enhance the TC of the base liquid [1] as the TC of solids is orders of magnitude higher than that of liquids. However, large particles, due to their larger size than that of smaller ones can sediment, which is not desired in heat transfer process/fluids. To solve this challenge, new suspensions containing nanoparticles (NP), defined as nanofluids (NFs) [2], may offer possibilities to enhance heat-transfer characteristics of conventional heat exchange fluids. Compared to the micron scale particles (MP), NPs offer larger relative surface area, which may enhance heat-transfer properties of suspensions [2]. For this reason many researchers are actively working on NF systems to study their capabilities for use in heat transfer applications. By now different micro and nanostructured materials with several base liquids have been employed to fabricate NF/MF for heat transfer purposes. Carbon based materials, such as carbon nanotubes [3–4] or metallic/intermetallic compounds such as Ag [5], Cu [6–7], and ceramic compounds such as Al_2O_3 [8], Fe_3O_4 [9], CuO [10], TiO_2 [11], SiO_2 [12], CeO_2 [13], ZnO [14], mesoporous SiO_2 [15] and SiC [16] are some materials compositions that have been studied by different groups. A wide range of liquids such as water, ethylene glycol (EG) and mixture of water and EG (W/EG) can be used as base liquids. For fabrication of NFs/MFs two main techniques including two step and one-step method are commonly used. In a two-step method at first solid particles are synthesized, separated, dried and then dispersed in the base liquids [17]. In the one-step preparation method the NPs/MPs are formed directly in the base liquid [18–21]. Not only the composition of

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* Corresponding author at: Faculty of Life Sciences and Biotechnology, Department of Bioengineering and Bionanotechnology, Shahid Beheshti University, Evin, Tehran 19839, Iran.
E-mail addresses: n_nikkam@sbu.ac.ir (N. Nikkam), morteza.ghanbarpour@energy.kth.se (M. Ghanbarpour), rahmatollah.khodabandeh@energy.kth.se (R. Khodabandeh), toprak@kth.se (M.S. Toprak).

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Nomenclature

D	fractal index
K	thermal conductivity, W/mK
r_a	size of aggregates of the nanoparticles
r_p	primary size of nanoparticles
T	temperature, K

Greek letters

Ø	volume fraction
Ø_{m}	maximum particle packing
Ø_{a}	effective volume fraction
μ	viscosity, kg/ms

Subscripts

bl	base liquid
NF	nanofluid
MF	microfluid
NP	nanoparticle
MP	microparticle
fr	freezing point

particulate materials influences the thermo-physical properties of NFs/MFs but also other factors, including particle morphology (size and shape), concentration and their extent of agglomeration, type of base liquid, NF/MF preparation method, stability of suspension and surfactants that may affect the TC and viscosity of NFs/MFs. Among all factors although the role of particle size as well as base liquid on thermo-physical properties of NFs/MFs is incontestable, their effect on TC and viscosity has not been studied in detail. Number of studies in this regard is limited and sometimes there is big discrepancy in the reported data [22]. The literature survey on effect of particle size and base liquid on thermo-physical properties of NFs/MFs reveal some challenges. First of all experimental data in the literature are very limited. Secondly the reported data; particularly for TC, are widely varied and inconsistent [23]. Moreover, in the earlier studies, due to the use of additives/surfactants for stabilization purposes the study of real impact of particle size as well as base liquid effect on TC and viscosity has become complicated. About the impact of base liquid the literature review shows, not only the number of investigations is limited but also its role on TC and viscosity of NFs is still under debate. Xie et al. [24–25] studied NFs with Al_2O_3 NPs in different base liquids and demonstrated that enhancement in TC of NFs take places if base liquid with lower TC is employed. Timofeeva et al. [26] studied SiC NFs in water (W) and W/EG mixture with controlled concentration, particle sizes and pH. Their investigations revealed that the TC enhancement is higher in W/EG based NFs compared to the same NFs with water base liquid. We recently studied the effect of base liquid on TC and viscosity by fabrication and thermo-physical properties evaluation of two NF systems containing the same α-SiC NP concentration but with different base liquids of water and W/EG mixture [27]. Our results showed the W/EG based NFs exhibited higher efficiencies as heat transfer fluids than the similar water based NFs. About the effect of particle size on TC and viscosity of NFs, some studies indicate that the TC enhancement of NFs is improved when smaller NPs is used [28] while some other works report the reverse trend [29]. Hence, there is a serious need to perform systematic investigation on the effect of particle size as well as base liquid on thermo-physical properties of NFs. For this purpose, we designed and performed a systematic work to study the role of these factors (particle size and base liquid effects) on TC and viscosity of NFs. We recently studied the fabrication and thermo-physical properties evaluation of EG and DEG based Cu NFs/MFs using two-step method at 20 °C [6–7]. Other factors including Cu NP/Cu MP compositions, the ranges of particle size, particle concentrations and the NFs/MFs fabrication procedure are kept the same for a direct comparison. Therefore, Cu NPs/MPs with different range of size were stabilized in EG and DEG via a two-step method and their TC and viscosity were analyzed. In this study we reviewed and focused on comparison between TC and viscosity properties (experimentally and theoretically) achieved by this work and our earlier reports on EG and DEG based suspensions [6–7] to study the base liquid effect. Moreover, the effect of particle size (nanoscale vs micron) on TC and viscosity of suspensions for both EG and DEG base liquids has been compared and discussed. Maxwell predictive correlation and Corcione model were applied to estimate the TC of Cu NFs and Cu MFs. Other comparison was performed to compare the experimental data and estimated values for viscosity of NFs/MFs using Einstein equation and Kriger-Dougherty correlation. Our findings on the physico-chemical and thermo-physical properties at different temperatures are presented in detail.

2. Experimental details

2.1. Materials and methods

Cu NPs and MPs with respective sizes in the range of 20–40 nm and 0.5–1.5 μm, were purchased from Alfa Aesar, Germany. DEG and EG (99.8%) were purchased from Sigma Aldrich, Germany. The use of dispersant/additive was avoided to study the real impact of Cu NPs/MPs. Cu NFs/MFs were prepared by adding of a known weight of Cu NPs/MPs in EG and DEG as the base liquids and Ultrasonic mixing of the suspension (Chemical instruments AB, CiAB, Sweden) for 25 min. A series of stable Cu NFs/MFs with concentration of 1 wt%, 2 wt% and 3 wt% were obtained (see Table 1 for details). All suspensions were stable for at least 36 h without any visual precipitation.

2.2. Characterization techniques

Scanning Electron Microscopy (SEM) analysis of Cu NPs/MPs was performed by using FEG-HR SEM (Zeiss-Ultra 55) system. Transmission Electron Microscopy (TEM) analysis of the Cu particles size and morphology were performed using JEOL 2100 at 200 kV acceleration voltage. Average solvodynamic particle size distribution of Cu NP/MPs was estimated by Beckmann-Coulter Delsa Nano C system. The TC of NFs/MFs was evaluated using TPS 2500 instrument, which works based on Transient Plane Source (TPS) method [30]. The validity of the TPS instrument was checked by comparing with a standard source for thermodynamic properties of water (IAPWS reference) and compared to

Table 1
Details of fabricated EG and DEG based Cu NFs/MFs.

Sample ID	NP ID	Base Liquid	NP loading	
			(vol%)	(wt%)
Cu-EG-NS-1 wt%	Cu NP	EG	0.11	1
Cu-EG-NS-2 wt%	Cu NP	EG	0.22	2
Cu-EG-NS-3 wt%	Cu NP	EG	0.33	3
Cu-EG-MS-1 wt%	Cu MP	EG	0.11	1
Cu-EG-MS-2 wt%	Cu MP	EG	0.22	2
Cu-EG-MS-3 wt%	Cu MP	EG	0.33	3
Cu-DEG-NS-1 wt%	Cu NP	DEG	0.11	1
Cu-DEG-NS-2 wt%	Cu NP	DEG	0.22	2
Cu-DEG-NS-3 wt%	Cu NP	DEG	0.33	3
Cu-DG-MS-1 wt%	Cu MP	DEG	0.11	1
Cu-DEG-MS-2 wt%	Cu MP	DEG	0.22	2
Cu-DEG-MS-3 wt%	Cu MP	DGE	0.33	3

the reference, the accuracy of measurement for distilled water was within ± 2% [31]. Finally, the viscosity of NFs/MFs was assessed using DV-II + Pro- Brookfield viscometer and the validity of this equipment was also verified using distilled water. The accuracy of measurement was obtained within ± 4% [31].

3. Results and discussion

3.1. Structural analysis

In order to study the crystal structure of the Cu NPs/MPs, X-ray diffraction (XRD) analysis was carried out and the result has been reported earlier [7], where commercial Cu NPs and MPs revealed major phase of metallic Cu (ICDD no: 01-085-1326). Furthermore, traces of CuO were observed in both Cu NPs and Cu MPs. (ICDD no: 061323). This oxide phase is most likely inherent to the procedures utilized for fabrication these commercial NPs/MPs.

3.2. Morphology analysis

Morphology of Cu NPs and MPs were analyzed by SEM and TEM: the micrographs are shown in Fig. 1 (a–d). As it can be seen from SEM images in Fig. 1(a) and (b), Cu NPs and MPs have spherical morphology, with estimated sizes in the range of 20–40 nm and 0.5–1.5 µm, respectively. TEM micrographs of Cu particles, presented in Fig. 1(c) and (d), displayed near spherical morphology of Cu for both NPs and MPs with the average size of about 20 nm and 0.65 µm for NPs and MPs, respectively. Selected are electron diffraction (SAED) patterns of NPs/MPs samples were indexed for Cu phase (Fig. 1(e) and (f)). Moreover, traces of CuO were observed in ED as was also revealed in XRD analyses (Fig. 1).

3.3. Dynamic Light Scattering (DLS) analysis

Dynamic Light Scattering (DLS) analysis was performed for Cu NPs/MPs in both base liquids to analyze the dispersed size of NPs/MPs in EG and DEG: the results are presented in Fig. 2 for both MFs and NFs. The size of Cu MPs and Cu NPs in EG medium was estimated in the range between 500 and 1400 nm and 40–1600 nm with an average solvodynamic size of 900 nm and 420 nm, respectively [6–7]. DLS analysis was also performed in EG media for Cu MPs and Cu NPs. The estimated sizes were observed in the range of 400–3500 nm and 30–1900 nm with an average solvodynamic size of 1400 and 460 nm, respectively. A comparison between DLS analysis estimated for EG and DEG media shows that narrowest particle size distribution was obtained for Cu MP in DEG media. Moreover, the smaller average solvodynamic size for Cu NP/Cu MP was achieved in DEG media. This may indicate that DEG has better dispersion property than EG for the particles used in this work. Obtaining such a big difference between primary size achieved from SEM and solvodynamic size measured by DLS shows that Cu NPs/Cu MPs are agglomerated or aggregated in base liquids. In order to distinguish that DLS analysis in water was carried out as well. The result (data not shown) revealed larger solvodynamic sizes than that in EG and DEG indicating the presence of Cu NP and Cu MP aggregates in base liquids due to their fabrication process.

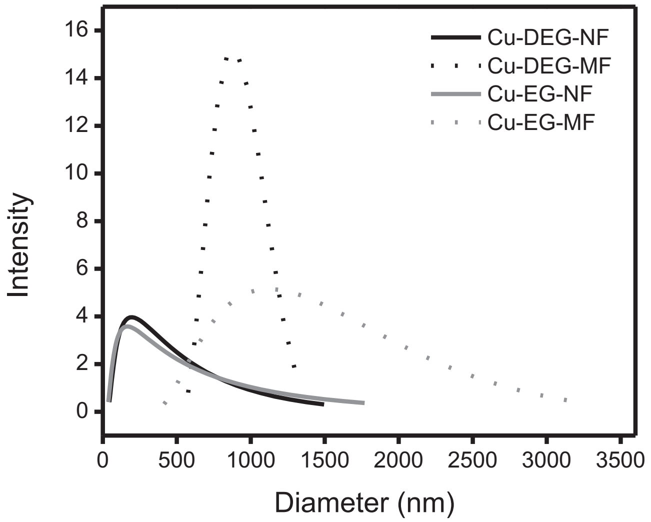

Fig. 2. Solvodynamic particle size distribution, via DLS, of Cu MPs, and Cu NPs in DEG and EG.

3.4. Thermo-physical properties evaluation of Cu NFs/MFs

The TC and viscosity of NFs/MFs are two major thermo-physical properties that are affected by the addition of NPs into the base liquid. Hence, the efficient NFs/MFs for use in heat transfer purposes not only should demonstrate effective thermal transport characteristics such as enhanced TC, but also exhibit minimal viscosity increase. Therefore, the desired goal is fabrication of suspensions with the highest possible TC

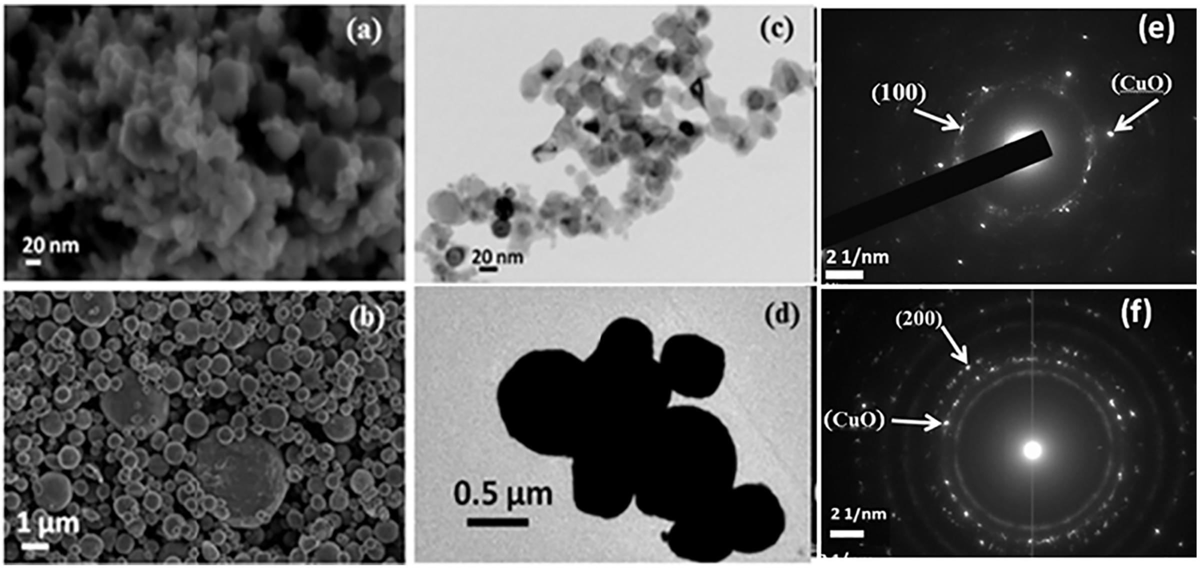

Fig. 1. (a, b) SEM micrographs; (c, d) TEM micrographs; and (e, f) electron diffraction patterns of Cu NPs and Cu MPs, respectively.

enhancement while a minimal impact on viscosity is favorable. TC and viscosity tests were carried out to assess the heat transfer capability of the fabricated NFs/MFs. For this purpose, several EG and DEG base Cu NFs/ MFs (12 samples) with various Cu NPs/Cu MPs concentration from 1 wt% to 3 wt% were evaluated for their TC and viscosity properties. The results for relative TC of samples $[(K_{nf}/K_{bl} - 1) * 100]$ at 20 °C and 40 °C are presented in Fig. 3(a) wherein K_{nf} and K_{bl} stand for TC of NFs/MFs and the base liquid, respectively. For NFs/MFs systems with both base liquids of EG and DEG, the TC enhancement improved with increasing concentration of Cu NPs/Cu MPs. As Fig. 3 (a) displays the suspensions containing Cu NPs (Cu NFs) with both EG and DEG base liquids exhibit higher TC enhancement compared to the samples with Cu MPs (Cu MFs) at the same particle concentration and temperature. It indicates the positive impact of using nanostructured materials rather than micro size particles. The reason is not clear yet but may be attributed to the higher surface area of Cu NPs compared to Cu MPs. Moreover, based on Fig. 3(a), compared to the DEG based samples, NFs/MFs with EG base liquid revealed higher TC enhancement. Therefore, as base liquid effect, EG based suspensions showed higher efficiencies as heat transfer fluids than the similar dispersions with DEG. The viscosity measurements were also carried out in order to study the rheological behavior of NFs/MFs with particle concentration ranging from 1 wt% to 3 wt% at 20 °C. All NFs/MFs exhibited Newtonian behavior which means the viscosity as a function of shear rate is constant. Fig. 3(b) displays the relative viscosity of NFs/MFs (μ_{nf}) to the viscosity of base liquid (μ_{bl}) at 20 °C. NFs containing Cu NPs with both EG and DEG base liquids exhibit higher increase in viscosity compared to the MFs containing Cu MPs, which may be related to the large contact/interface area between Cu NPs and base liquids. One important finding is that for DEG base liquid [6] for all Cu NFs/Cu MFs, the values of TC enhancement $[(K_{nf} - K_{bl} - 1) * 100]$ was lower than the increase in viscosity values $[(\mu_{nf}/\mu_{bl} - 1) * 100]$. However, for EG based NFs/MFs, all samples showed higher TC enhancement values than their increase in viscosity. It may reveal the effect of base liquid affecting the TC and viscosity of NFs/MFs. As a result and among all NFs/MFs with different base liquids of EG and DEG, the maximum TC enhancement of ~4.7% with viscosity increase of ~1.8% was obtained for EG based Cu NFs with 3 wt% Cu NPs at 20 °C. It shows that this NF system may have potential for use in some heat transfer applications where there is no issue originated from pressure drop. There are few studies in the literature reporting on TC of EG and DEG base Cu NFs. Most of the reports are based on fabrication of Cu NFs via one-step preparation method [18–21]. Eastman et al. [18] reported a 1.5% enhancement in TC for around 0.5 wt% Cu-EG NF using one-step preparation method. Zhu et al. [19] fabricated Cu NF by reducing a mixture of copper sulfate pentahydrate in EG with sodium hypophosphite monohydrate. They used polyvinylpyrrolidone (PVP) as a surfactant and reported almost 9% TC enhancement containing ~0.9 wt% Cu NP concentration. However, in that report the impact of PVP on the TC of Cu NF was neglected. As described before in our work to study the real impact of Cu NP/MP on TC and viscosity of NFs/MFs, the use of surfactant or any additives was avoided. Compared to the EG based Cu NFs reported by Eastman et al. [18], Zhu et al. [19], our NFs/MFs exhibited lower TC enhancement. The possible reasons for obtaining different results can be due to use of different preparation method (one-step vs two-step route), different measurement instrument (THW vs TPS method) [32] and surfactants or any additives used for stabilization purposes. Moreover, the existence of traces of CuO in both Cu NPs and Cu MPs may play as a barrier in heat transfer mechanisms [7]. We also recently studied on synthesis of Cu NF with DEG base liquid using one-step method (microwave-assisted route) and reported 6% TC enhancement for DEG Cu NF containing 0.8 wt% Cu NP concentration [21]. This value also is higher than that of our present results for EG and DEG based NFs/MFs even at lower Cu NP concentration. Using an advanced one-step preparation method (microwave-assisted route), impact of surface modifier (PVP) or other additives may account for some of the differences. We already reported 2.8% TC enhancement for Cu NF with DEG base liquid [6]. A comparison between the TC enhancements of 3 wt% Cu-EG NF at 20 °C in the present investigation (~4%) and our earlier report [6] for the Cu NF with the same Cu NP concentration but with DEG base liquid (relative TC of ~2.8%), fabricated by two-step method (both measured by TPS method) showed that our present result is 30% higher than that of NF with DEG base liquid. This is ascribed to the effect of the base liquid.

3.5. Comparison between experimental results and predictive models for TC of NFs/MFs

In order to estimate TC of NFs/MFs, Maxwell effective medium theory [34] and Corcione model [35] were used. The relative TC predicted by Maxwell effective medium theory is described by Eq. (1):

$$\frac{K_{nf}}{K_{bl}} = \frac{K_p + 2K_{bl} + 2(K_p - K_{bl})\emptyset}{K_p + 2K_{bl} - (K_p - K_{bl})\,\emptyset} \tag{1}$$

wherein, K_{bl}, K_p, and K_{nf} are the TC of base liquid, NP/MP and NF/MF, respectively. $\emptyset$ is the volume fraction of NP/MP. This expression for TC enhancement is only applicable for spherical particles, does not take into account the thermal interface resistance between the liquid and particles and the effect of particle size. We also used other predictive model to estimate the TC of NFs/MFs namely Corcione model [35]. This model takes into account the particle size in estimation of TC of NFs/MFs which has been neglected in Maxwell effective medium theory.

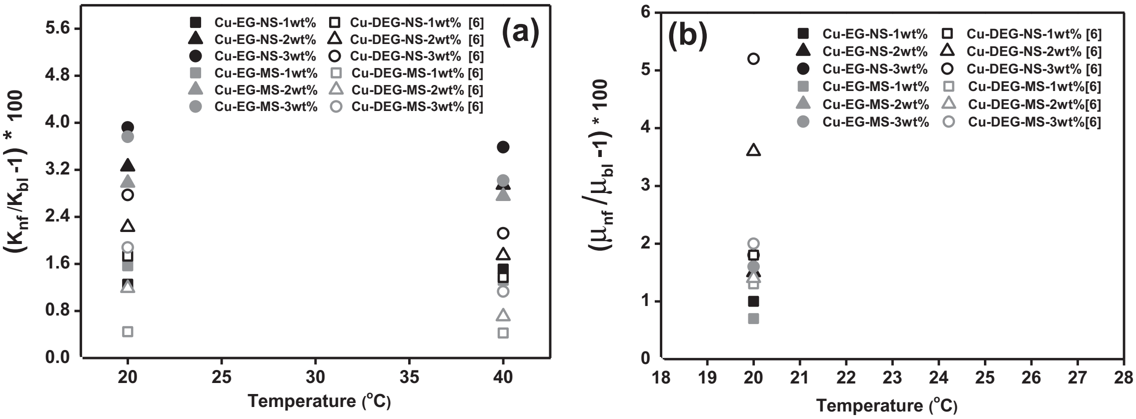

Fig. 3. (a) Relative TC of Cu NFs/MFs with various concentration of Cu NP/MP at different temperatures and (b) Relative viscosity of Cu NFs/MFs with various concentration of Cu NP/MP at 20 °C.

$$\frac{K_{nf}}{K_{bl}} = 1 + 4.4\, R_e^{\,0.4}\, P_r^{\,0.66} \left(\frac{T}{T_{fr}}\right)^{10} \left(\frac{K_p}{K_{bl}}\right)^{0.03} \varnothing^{0.66} \tag{2}$$

In the formula, *Re* is the Reynolds number of particles, *Pr* stands for the Prandtl number, T is the NF temperature, T_{fr} is the freezing point of the base liquid, K_{nf}, K_p and K_{bl} are the TC of NF/MF, NP and base liquid, respectively. $\varnothing$ is the volume fraction of the suspended particles. In more detail, the particles *Re* number and the *Pr* number for the base liquid are defined as:

$$R_e = \frac{\rho_f u_B d_p}{\mu_{bl}} \tag{3}$$

$$Pr = \frac{\mu\, C_P}{K} \tag{4}$$

where ρ_f and μ_{bl} are the mass density and the dynamic viscosity of the base liquid, respectively. d_p and u_B are the particle diameter and mean Brownian velocity, respectively. Assuming absence of agglomeration, the NP Brownian velocity u_B is calculated according to Keblinski et al. [36]:

$$u_g = \frac{2k_b T}{\pi \mu_{bl} d_P^{\,2}} \tag{5}$$

wherein k_b and T are the Boltzmann's constant and temperature, respectively. Both the experimental data and estimated values using Maxwell effective medium theory and Corcione model are plotted in Fig. 4. For all NFs/MFs (except for DEG based MF at 40 °C), Maxwell underestimates the TC of NFs/MFs. It shows the importance of other factors such as particle size as well as interface between particles and base liquid which may affect the TC of NFs/MFs, however have been neglected in the Maxwell theory. Based on Fig. 4(a) and (c) the TC of EG and DEG based NFs (Cu DEG-NS and CEG NS) is well estimated by Corcione model at 20 °C. This model could also predict the TC of EG base MFs at the same temperature while overestimates the TC of both EG and DEG based Cu NF/MF at 40 °C (Fig. 4(b) and (d)) may be due to the Brownian motion at higher temperature. Moreover, based on Fig. 4(b) and (d) Corcione model could estimate relatively well the TC of MF at 40 °C while overestimate at 20 °C. In summary, the model developed by Corcione is applicable for our fabricated EG and DEG based Cu NF containing Cu NP at 20 °C. It is also proper for use at higher temperature (40 °C) for both EG and DEG based MF containing Cu MP.

3.6. Comparison between experimental results and estimated values for viscosity of Cu NFs/MFs

To predict the relative viscosity of NFs/MFs, Einstein law of viscosity [37] and Krieger–Dougherty model [38] were applied. Eqs. (6) and (7) describes the Einstein law of viscosity and Krieger–Dougherty model, respectively:

$$\mu_{f/}\mu_{bl} = 1 + 2.5\ \varnothing \tag{6}$$

$$\mu_f = \mu_{bl}\left(1 - \frac{\varnothing_a}{\varnothing_m}\right)^{-\eta \varnothing_m} \tag{7}$$

wherein $\varnothing_a$ was suggested by Chen et al. [39] as given in Eq. (8):

$$\boldsymbol{\varnothing_a} = \varnothing\left(\frac{\boldsymbol{r_a}}{\boldsymbol{r_p}}\right)^{3-D} \tag{8}$$

Where μ_{bl} and μ_{nf} are the viscosity of the base liquid and the NF/MF, respectively. $\varnothing$ is the volume fraction of the particles, r_a is effective

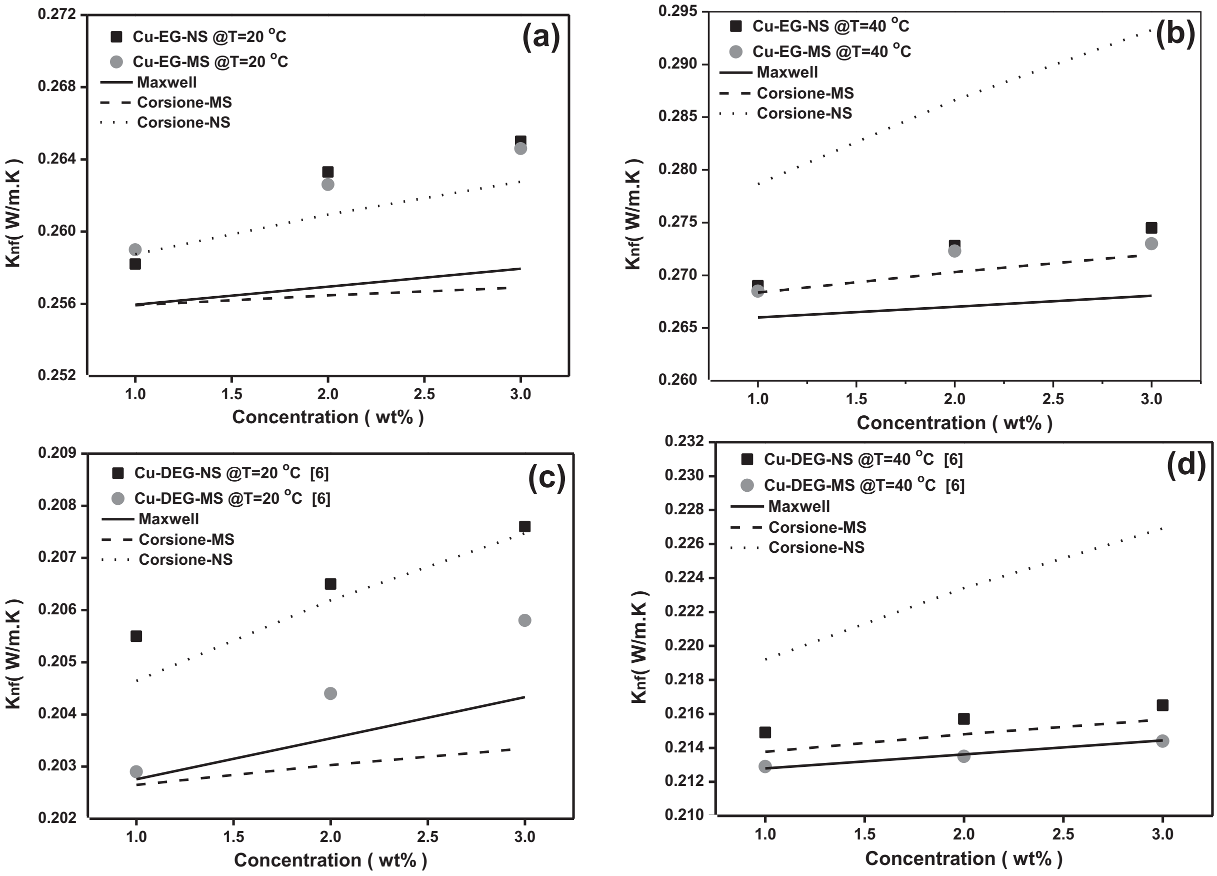

Fig. 4. TC values predicted by Maxwell and Corcione models for (a) EG based NFs/MFs at 20 °C (b) EG based NFs/MFs at 40 °C (c) DEG based NFs/MFs at 20 °C and (d) EG based NFs/MFs at 40 °C.

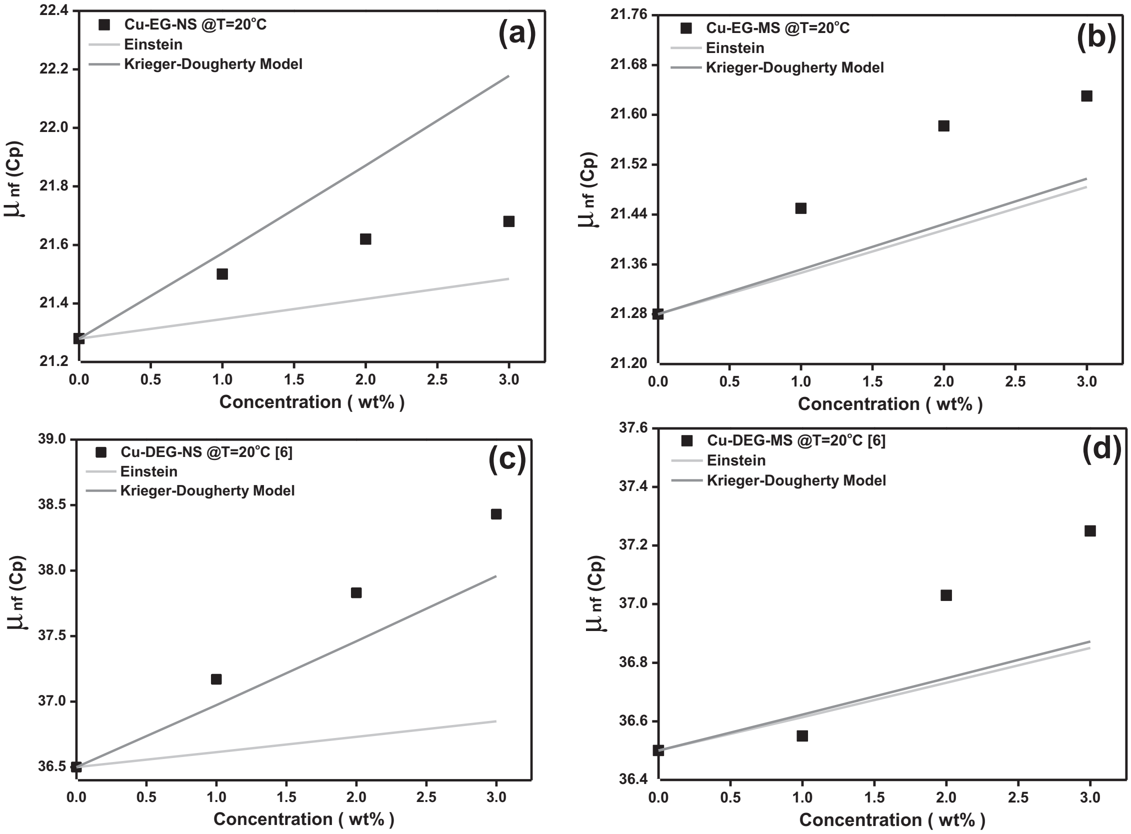

Fig. 5. Estimated viscosity values from Einstein equation and Krieger–Dougherty model for (a), (b) EG based NFs/MFs and (c), (d) DEG based NFs/MFs; all at 20 °C.

aggregate size of the NPs in base liquids media estimated by DLS and r_p is the primary size of NPs obtained from SEM. $\varnothing_m$ is the maximum particle packing fraction has a value of 0.605 [40]. η is the intrinsic viscosity and its value typically is 2.5 [41]. $\varnothing_a$ is the effective volume fraction of aggregates and D is the fractal index which is typically 1.8 for particles [42]. Both experimental values and the predicted data for viscosity of NFs/MFs with EG and DEG base liquids using Einstein equation and Krieger–Dougherty model are plotted in Fig. 5. Fig. 5 (a) for EG based NF Einstein equation underestimates the viscosity of the tested NFs. In the same figure although, Krieger–Dougherty model predicts well in lower concentration of Cu NP, it overestimates the viscosity of the NFs particularly in higher Cu NP concentrations. Fig. 5 (b) displays relative viscosity of EG based Cu MF (suspension containing Cu MPs) at various particle concentration. Einstein equation as well as Krieger–Dougherty model underestimate the viscosity of Cu MFs. When it comes to DEG based suspensions, while Einstein equation underestimates the viscosity of NFs containing Cu NP, the Krieger–Dougherty model predicts well (Fig. 5 (c)). Based on Fig. 5 (d) for MFs containing Cu MPs, both Einstein equation and Krieger–Dougherty model underestimate the viscosity of MFs; however, they predict well in lower concentrations ($\leq$ 1%). In summary Einstein equation underestimated the viscosity of NFs and MFs (except at lower concentrations for DEG based MFs). Krieger–Dougherty model could estimate well the viscosity of DEG based Cu NF at 20 °C.

4. Conclusions

We presented on the fabrication and physico-chemical and thermophysical properties evaluation of EG and DEG based NFs/MFs containing Cu NPs/MPs intended for heat transfer applications. SEM analysis revealed spherical particle morphology with an average size of 20–40 nm and 05–1.5 μm for NPs and MPs, respectively. A two-step method was employed to fabricate stable NFs/MFs. For all Cu NFs/MFs enhancement of TC over the base liquid was observed due to the presence of Cu NPs/MPs. Rheological behavior of samples was evaluated by measuring the viscosity of NFs/MFs. All Cu NFs/MFs exhibited Newtonian behavior in the tested temperature and the viscosity of suspensions increased with increasing Cu NP/MP concentration. Our experiments on the effect of particle size showed that suspensions containing Cu NPs (Cu NFs) exhibited higher TC enhancement compared to the samples with Cu MPs (Cu MFs). Moreover, compared to the DEG based samples, NFs/MFs with EG base liquid revealed higher TC enhancement, which reveal EG based suspensions are more beneficial for use as heat transfer fluids than the similar samples with DEG base liquid. For all Cu NFs/MFs with EG base liquid, the values for TC enhancement were higher than the increase in viscosity while the reverse trend was observed for DEG based NFs/MFs. Among all Cu NFs/MFs with EG and DEG based liquids, Cu NF containing 3 wt% Cu NP with EG base liquid (Cu-EG-NS-3 wt%) exhibited most promising results with $\sim$4.7% TC enhancement while $\sim$1.8%viscosity increase was observed (at 20 °C). It indicates the potential of this kind of NF to be used in some heat transfer applications. While Maxwell theory underestimated the TC of NFs/MFs, the TC of NFs/MFs estimated well by Corcione model of at 20 °C. Einstein equation underestimated the viscosity of NFs and MFs while Krieger–Dougherty model could estimate well the viscosity of some NFs at 20 °C.

Acknowledgments

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