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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

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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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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

$\varnothing$	volume fraction
$\varnothing_m$	maximum particle packing
$\varnothing_a$	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