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Experimental study on preparation and base liquid effect on thermo-physical and heat transport characteristics of α-SiC nanofluids☆

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ABSTRACT

Nanostructured solid particles dispersed in a base liquid are a new class of nano-engineered colloidal solutions, defined with a coined name of nanofluids (NFs). These fluids have shown potential to enhance heat transfer characteristics of conventional base liquids utilized in heat transfer application. We recently reported on the fabrication and thermo-physical property evaluation of SiC NF systems, containing SiC particles with different crystal structure. In this study, our aim is to investigate the heat transfer characteristics of a particular α-SiC NF with respect to the effect of α-SiC particle concentration and different base liquids on the thermo-physical properties of NFs. For this purpose, a series of NFs with various α-SiC NPs concentration of 3, 6 and 9 wt.% were prepared in different base liquids of distilled water (DW) and distilled water/ethylene glycol mixture (DW/EG). Their thermal conductivity (TC) and viscosity were evaluated at 20 °C. NF with DW/EG base liquid and 9 wt.% SiC NP loading exhibited the best combination of thermo-physical properties, which was therefore selected for heat transfer coefficient (HTC) evaluation. Finally, HTC tests were performed and compared in different criteria, including equal Reynolds number, equal mass flow rate and equal pumping power for a laminar flow regime. The results showed HTC enhancement of NF over the base liquid for all evaluation criteria; 13% at equal Reynolds number, 8.5% at equal volume flow and 5.5% at equal pumping power. Our findings are among the few studies in the literature where the heat transfer enhancement for the NFs over its base liquid is noticeable and based on a realistic situation.

1. Introduction

New advanced suspensions containing solid nanoparticles (NPs) in traditional heat transfer fluids such as distilled water (DW), ethylene glycol (EG) or their mixture (DW/EG) are called nanofluids (NFs) [1]. These dispersions have become attractive due to their potential benefits and applications in cooling industry, such as cooling of electronics, transport vehicles, data centers, and power generation devices [2–4]. For more than hundred years since Maxwell [5], scientists and engineers have made great investigations to improve the thermal conductivity (TC) of traditional heat-exchange fluids by dispersing millimeter- or micrometer-sized particles in base liquids. Nevertheless, the major problems with the use of such large particles are the rapid settling of these particles, clogging the miniature channels, increased abrasion, and much increase in the pumping power [6,7]. Due to small sizes and very large specific surface areas of the NPs, NFs may have novel properties such as higher TC, minimal clogging during flow and improved HTC. These features of NFs have motivated many scientists to study the heat transfer performance and flow characteristics of various NFs with different NPs and base liquids. There are several studies in the literature using different NF formulations and comparing their HTC with that of the corresponding base liquid. So far different types of NPs such as metallic and ceramic NPs have been used to prepare NFs and their heat transfer characteristics have been studies. Detailed literature reviews of the heat transfer behavior of NFs have been provided by Yu et al. [8] and Murshed et al. [9]. Ceramic NPs are more favorable than metallic NPs, as they incorporate much easier into the base liquid. They also exhibit better chemical stability over long period of times compared to metal NPs [10]. However, ceramics generally have low TCs with few exceptions such as SiC NPs which have one of the highest TC (TC value for α-type SiC is 490 W/m K) [11]. Additionally, these materials are commercially available for the fabrication of NFs via two-step method, wherein NPs are acquired

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and then dispersed in the base liquids [6]. Therefore, α-SiC NPs can be a promising candidate for fabrication of efficient NF for heat transfer applications. Although there are limited studies on TC and/or viscosity of SiC NFs with different base liquids [10,12–15], few studies have reported on heat transfer characteristics of α-SiC NFs. Timofeeva et al. [14,15] investigated α-SiC NFs with water and DW/EG base liquids, where they showed the effect of different factors on the thermo-physical properties of α-SiC NFs—including TC and viscosity of NFs, and also the HTC of DW/EG and water based suspensions with α-SiC NPs. Their investigation on water-based α-SiC NFs showed that the increases in TC were high but the increase in the viscosity with the introduction of 4.1 vol.% (~13 wt.%) α-SiC NPs led to a reduction in HTC, being up to 15% worse than that of water as the base liquid (at equal velocity) [14]. Although using larger particle sizes and pH adjustment significantly decreased the viscosity of suspensions, still for water based α-SiC NFs the HTC was just slightly higher than that of base liquid [14]. When they changed the base liquid of NF to the DW/EG mixture with a 50/50 volume ratio (at the same 13 wt.% SiC NP loading), 14.2% enhancement on the HTC of NFs was obtained for a turbulent flow regime at 71 °C [15] while water based NFs were scarcely comparable with that of base liquid. We recently studied on the fabrication and thermo-physical property evaluation of four different DW/EG based (50/50 weight ratio) SiC NF systems fabricated by dispersing SiC NPs with different crystal structures of α- and β-types (9 wt.% α- and β-SiC NFs) [16]. The results revealed that among all suspensions, NF with particular α-type SiC particles exhibited better combination of thermo-physical properties by TC enhancement of ~20% with only 14% increased viscosity as compared to the respective base liquid. This indicated the capability of this particular NF for further heat transport characteristic investigations including HTC tests.

The effect of base liquid on the thermo-physical properties including TC and viscosity of NFs is not well investigated and understood in the literature yet. There are few reports in the literature indicating some general trends about the effect of the base liquid; Xie et al. [17,18] fabricated suspensions with the same Al_2O_3 NPs in EG, water, glycerol and pump oil and showed an increase in the relative TC value of NFs with a decrease in the TC of the base liquid. Tsai et al. [19] reported that the alteration of the base liquid viscosity (from 4.2 to 5500 cP, by mixing two base liquids with approximately the same TC) resulted in a decrease in the TC of the Fe_2O_3 NFs as the viscosity of the base liquid increased. Timofeeva et al. [15] investigated comparatively SiC NFs in water and DW/EG mixture with controlled concentration, particle sizes and pH. Their investigations showed that the relative change in TC due to the addition of 4.1 vol.% (13 wt.%) α-SiC NPs is around 5% higher in DW/EG compared to their achieved result in water [14]. In this work, our aim is to fabricate α-SiC NFs and investigate the effect of the base liquid and α-SiC NP concentration on the thermo-physical and transport characteristics of these NFs including HTC test. For this purpose, stable α-SiC NFs with various NP loading and two different base liquids (distilled water and DW/EG) were fabricated. The base liquid was a mixture of DW/EG (50:44.5 by vol.%; 50:50 weight ratio). The thermo-physical properties of NF including TC and viscosity were measured at 20 °C. Finally, HTC tests were performed and compared in different criteria such as equal Reynolds number, mass flow rate and pumping power for the α-SiC NF with optimum properties in a laminar flow regime.

2. Experimental

2.1. Materials and methods

Silicon carbide (SiC) particles with an alpha type crystal structure (α-SiC) were purchased from Superior Graphite (USA) and were utilized to fabricate a series of NFs with 3 wt.%, 6 wt.% and 9 wt.% NP loading. For this purpose, α-SiC NPs were dispersed in distilled water (DW) as the base liquid (two-step method preparation) to obtain 9 wt.% SiC NF. Then the suspension was mixed by ultrasonic mixing and the pH of NFs was adjusted to ~9.5 in order to obtain stable NFs—where SiC NPs have a highly negative surface charge as detailed in Ref. [16]. NFs with 6 wt.% and 3 wt.% α-SiC NPs were prepared by diluting the 9 wt.% NF with a proper amount of DW. This is done to assure that the processing history of the samples is identical. In order to fabricate DW/EG (50/50% by wt.%) based α-SiC NFs, the same fabrication procedure was followed, using DW/EG as the base liquid, so that three NFs with varying α-SiC NPs were prepared. All NFs (Table 1) were stable for more than two weeks without any visual precipitation. Since one of our aims was to study the real effect of α-SiC NPs on the thermo-physical properties of NFs, the use of surfactant/surface modifiers was strictly avoided.

2.2. Characterization techniques

Powder X-ray diffraction (XRD) was performed to identify the crystal structure of the material, using a Philips X'pert pro super Diffractometer with Cu Kα source (λ = 1.5418 Å). Scanning electron microscopy (SEM) analysis of α-SiC particles was performed by using FEG-HR SEM (Zeiss-Ultra 55). Average solvodynamic particle size distribution was evaluated by Beckmann-Coulter Delsa Nano C system. TC of NFs was measured by using TPS 2500 instrument (HotDisk model 2500), which works based on the transient plane source (TPS) method. The validity of the TPS instrument was checked by comparing with a standard source for the thermodynamic properties of water (IAPWS reference) and compared to the reference the accuracy of measurement for distilled water was within 2%—as described earlier [20]. Finally, the viscosity of NFs was evaluated using a DV-II + Pro-Brookfield viscometer. A closed-loop system was used to perform HTC tests, using the setup presented in detail in [21].

3. Results and discussion

3.1. Structure and morphology analysis

SiC material exists in various crystalline forms; two major crystal structures are cubic and hexagonal [22]. It is important to identify the crystal phase of SiC; therefore, X-ray diffraction (XRD) analysis was carried out on as-received NPs. Fig. 1(a) displays the powder XRD pattern of SiC NPs, which is indexed for the hexagonal crystal structure of SiC (JCPDS # 01-073-1663), namely α-SiC. The morphology of the particles was analyzed by scanning electron microscopy (SEM) and a micrograph is shown in Fig. 1(b). There is a wide size dispersion, which makes it quite difficult to estimate the size of α-SiC NPs from the micrographs; nevertheless, a rough estimation was performed by counting more than 200 particles resulting in an average particle size of 115 ± 35 nm.

3.2. Dynamic light scattering (DLS) analysis

DLS analysis was performed to estimate the dispersed size of SiC NPs in base fluid, in order to understand the influence of the effective size of dispersed NPs in the base liquid. DLS analysis results are shown in Fig. 2 for NFs in distilled water and DW/EG media. A wide range of particle size distribution (150–4500 nm) with an average peak value of ~1290 nm

Table 1
Details of fabricated α-SiC NFs.

Sample ID	NP ID	Base liquid	NP loading	
			(vol.%)	(wt.%)
α-SiC NF-DW/EG-3 wt.%	α-SiC NP	DW/EG (50:44.5) by vol.%	0.95	3
α-SiC NF-DW/EG-6 wt.%	α-SiC NP	DW/EG (50:44.5) by vol.%	1.9	6
α-SiC NF-DW/EG-9 wt.%	α-SiC NP	DW/EG (50:44.5) by vol.%	2.85	9
α-SiC NF-DW-3 wt.%	α-SiC NP	Distilled water	0.95	3
α-SiC NF-DW-6 wt.%	α-SiC NP	Distilled water	1.9	6
α-SiC NF-DW-9 wt.%	α-SiC NP	Distilled water	2.85	9