Journal of Colloid and Interface Science 364 (2011) 71–79

Contents lists available at SciVerse ScienceDirect

Journal of Colloid and Interface Science

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Improving the heat transfer efficiency of synthetic oil with silica nanoparticles

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ARTICLE INFO

Article history:
Received 3 May 2011
Accepted 1 August 2011
Available online 12 August 2011

Keywords:
Heat transfer fluid
Synthetic oil
Therminol
Nanofluid
Silica
Silicon oxide
Nanoparticles
Surfactant
Thermal conductivity
Viscosity
Total heat
Heat transfer efficiency
Cationic surfactant
Benzalkonium chloride

ABSTRACT

The heat transfer properties of synthetic oil (Therminol 66) used for high temperature applications was improved by introducing 15 nm silicon dioxide nanoparticles. Stable suspensions of inorganic nanoparticles in the non-polar fluid were prepared using a cationic surfactant (benzalkonium chloride). The effects of nanoparticle and surfactant concentrations on thermo-physical properties (viscosity, thermal conductivity and total heat absorption) of these nanofluids were investigated in a wide temperature range. The surfactant-to-nanoparticle (SN) ratio was optimized for higher thermal conductivity and lower viscosity, which are both critical for the efficiency of heat transfer. The rheological behavior of SiO_2/TH66 nanofluids was correlated to average agglomerate sizes, which were shown to vary with SN ratio and temperature. The conditions of ultrasonic treatment were studied and the temporary decrease of agglomerate size from an equilibrium size (characteristic to SN ratio) was demonstrated. The heat transfer efficiencies were estimated for the formulated nanofluids for both turbulent and laminar flow regimes and were compared to the performance of the base fluid.

1. Introduction

The operating temperatures in many process applications range from 150 °C to 400 °C, and the requirements to heat transfer fluids include stability, sufficient energy transfer and service ratings for the mechanical components. The use of proper heat transfer fluid can be safer and more efficient than steam, electrical, or direct fire heating methods and can provide more uniform heat delivery and removal. Amongst the high temperature heat transfer fluids the molecular structures of aromatic synthetic oils provide higher stability at elevated temperatures than hot oils (paraffinic hydrocarbons) or silicone oils. The synthetic oils also offer the highest thermal conductivity amongst the high temperature heat transfer fluids (~0.1 W/mK), but it is still very low compared to the thermal conductivity of water (~0.6 W/mK at room temperature), and it also decreases with increasing temperatures.

The introduction of nano-sized particles to heat transfer fluids (nanofluids) is an emerging thermal management concept with implications in many disciplines including power generation, transportation, microelectronics, chemical engineering, aerospace and manufacturing [1–10]. Nanoparticles have thermal conductivities that are significantly higher than base fluids. They also remain in suspension and contribute to the thermo-physical properties of the system while mitigating problems associated with erosion, sedimentation and clogging, observed for suspensions of micron size particles. A large variety of nanoparticle suspensions with different nanoparticle materials, shapes, sizes and concentrations have been extensively studied in last decade; the majority of studies have been conducted in polar base fluids such as water, ethylene glycol (EG) and their mixtures. However, there are just a few studies on nanofluids in organic and mineral oils for heat transfer applications [11–21].

The heat transfer coefficient (h) is used for evaluation and efficiency comparison of the heat transfer fluids. A fluid with a substantial heat transfer coefficient advantage may allow for the reduction in sizing of the system equipment, increase the production output, and/or reduce the energy costs. At a specific temperature, flow velocity, and pipe diameter, a fluid's heat transfer coefficient can be calculated using its density, viscosity, thermal conductivity and specific heat [22].

Although some work has been done with nanoparticle suspensions in organic fluids, the literature lacks studies on the effects of nanoparticle additions to the high temperature heat transfer fluids,

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doi:10.1016/j.jcis.2011.08.004

especially aromatic synthetic oils. In this study we assess the possible benefits of adding silicon dioxide nanoparticles and surfactant to an aromatic high temperature heat transfer fluid. The approaches to stabilization of silica nanoparticle suspensions in synthetic oils presented here can also be used to stabilize silica coated core/shell multifunctional nanoparticles, which exhibit great potential for future nanotechnologies. The effects of nanoparticle concentration and surfactant concentration on viscosity, thermal conductivity and total heat adsorption of suspensions were studied in a wide temperature range. The experimental data were used to estimate the heat transfer efficiency and to guide the optimization of the nanofluid composition for a better heat transfer performance.

2. Materials and methods

The silicon dioxide (silica) nanopowder (inset to Fig. 1) with average particle sizes of 15 nm (4850MR, NanoAmorphous Materials, Inc.) was dispersed in the synthetic heat transfer fluid Therminol 66 (TH66) (Solutia, Inc.). Benzalkonium chloride (BAC), benzethonium chloride (BZC), and cetyltrimethylammonium bromide (CTAB) (all from Acros Organics) were tested as a surfactant for dispersing silica. The volume (vol.) percentages of nanoparticles and surfactants refer to the volume of the resulting nanofluid, which is commonly used for the thermal conductivity analysis. Surfactants were dispersed into the base fluid first, followed by introduction of the nanopowder. The mixture was homogenized by continuous stirring with a magnetic bar and sonicated 10 times (~80 W output power, 50% duty cycle, Branson Sonifier S-450) for five minutes each time. Continuous ultrasonic treatment increased the temperature of suspensions, but it was monitored to stay below 65 °C (initial sonication conditions). The nanofluid was equilibrated to room temperature between the treatments. To investigate the effect of sonication conditions on the nanofluid properties the duration and the number of sonications were increased as described in the results section.

The sizes of nanoparticle agglomerates were approximated using the dynamic light scattering (DLS) at a 90° scattering angle with a 90Plus/BIMAS particle size analyzer (Brookhaven Instruments Corp., NY). All samples were diluted ~100–1000 times to avoid multiple scattering effects.

Scanning electron microscopy (SEM) was conducted using Hitachi S4700 microscope.

The effective thermal conductivity of nanoparticle suspensions was measured using the transient hot wire based thermal property analyzer (Model KD2pro, Decagon Devices, Inc.). The reported values represent the average of at least 20 measurements.

The viscosity of the nanofluids was measured at temperatures ranging from 15 to 135 °C using a Brookfield DV-II+ rotational type viscometer with the SC4-18 spindle (instrumental error ~2%) by Brookfield Engineering Laboratories, Inc.

The total heat adsorption by nanofluids and pure materials were measured using the differential scanning calorimeter Q20 (TA Instruments, Inc.). Measurements were performed in hermetic aluminum pans using ~5 mg of nanofluid sample with temperature scans between 35 and 250 °C with 10 °C per minute heating/cooling rate.

3. Results and discussion

3.1. Selection of the surfactant

The surfactants help to control the strength of particle–particle interactions and the dispersion/agglomeration of particles in suspension [23–25]. Dispersing inorganic nanoparticles (SiO_2) in a non-polar organic fluid (TH66) requires a surfactant that will adhere to oxide surfaces and also be miscible with the non-polar fluid. Accounting for the negative surface charges of silica [26] several cationic surfactants (BAC, BZC, and CTAB) were tested in the preliminary series. The amount of surfactant required to disperse silica was approximated from the total surface area per gram of nanoparticles using the adsorption model with "laying flat" (~0.02 M per 1 vol.% of 15 nm SiO_2) and compacted "standing up" (~0.06 M per 1 vol.% of 15 nm SiO_2) layers of the surfactant molecules. Suspensions with 1 vol.% of SiO_2 nanoparticles with no surfactant and excess of each surfactant (5 wt.% or ~0.12–0.14 M) were prepared using the aforementioned procedure. The visual appearance of suspensions 24 h after the last sonication

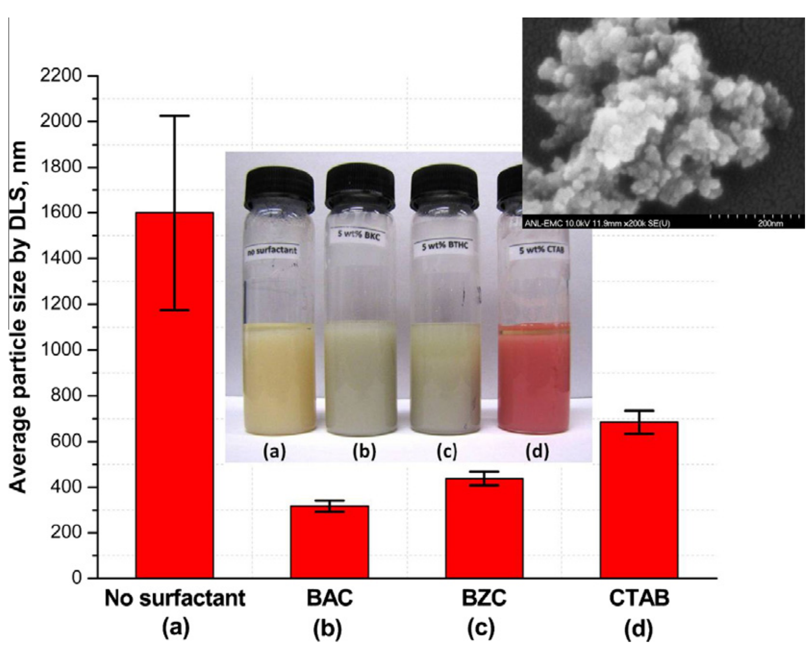

Fig. 1. Summary of DLS analysis of diluted SiO_2 dispersions in TH66 24 h after utrasonication; (a) no surfactant, (b) benzalkonium chloride, (c) benzethonium chloride, (d) cetyltrimethylammonium bromide. (Inset, middle) Visual appearance of 1 vol.% SiO_2/TH66 with various surfactants. (Inset, right) SEM image of SiO_2 powder used in preparation of nanofluids.