Sand-propylene glycol-water nanofluids for improved solar energy collection

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ABSTRACT

Experiments were carried out on the preparation, thermophysical properties' measurement and application of surfactant-free, sand-propylene glycol-water nanofluids for solar energy collection. Thermal conductivity enhancement of 16.3% and viscosity reduction of 47% were observed for 2 vol % sand-PG-water nanofluid at 28 °C. Microconvection caused by Brownian motion was identified as one of the mechanisms of thermal conductivity enhancement. The relative viscosity of sand-propylene glycol-water nanofluid was less than 1 over a temperature range of 10–60 °C and sand nanoparticle concentration range of 0.5–2 vol %. The lower viscosity of sand-PG-water nanofluids in comparison to that of propylene glycol-water mixture is attributed to non-covalent interactions between sand nanoparticles and propylene glycol, leading to perturbation of hydrogen bonding network. The use of 2 vol % sand-PG-water nanofluid resulted in enhancement of heat transfer and solar energy collection by 16.5%. Our results demonstrate that sand-PG-water nanofluids are suitable for use as heat transfer fluid in solar collectors.
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1. Introduction

Efficient heat transfer from the collector surface to the heat transfer fluid is important to harness solar energy through solar thermal systems. Hence, heat transfer intensification is expected to improve collection efficiency in these systems [1–3]. Intensification of heat transfer may also be achieved through the use of heat transfer media with superior transport properties compared to conventional coolants. Nanofluids are examples of such heat transfer media, with their thermal conductivities higher than those of liquids in which they are dispersed [4–7]. By virtue of their colloidal stability and well-dispersed nature of nanoparticles in them, they do not pose problems such as choking and wear [8–10], which are experienced with the suspension of micron-sized particles [11,12].

The subject of 'nanofluids' continues to evince research interest at-least on two major grounds: (i) the mechanisms for property modulation of nanofluids are still not completely understood with wide variation among reported literature data for the same systems [13,14] and (ii) the process for preparation of nanofluids, either by

one-step method [15–17] or two-step method [7,18–22], needs to be scaled up to enable preparation in large quantities required for real-time testing.

The application of nanofluids in harnessing solar energy has been reviewed [23–25], with majority of reviewed studies demonstrating the improved solar energy harvesting using nanofluids. Numerical investigation on the use of nanofluids in two-layer solar pond has revealed their superior solar energy capability than that of a conventional solar pond [2]. The nanoparticle concentration dependent increase in overall efficiency of photovoltaic thermal (PV/T) unit has been reported for silica-water nanofluid, with increased overall efficiency for 3 wt % nanofluid, when compared to that of 1 wt % nanofluid and water [26].

The oblique stagnation point flow for a Walter's B type nanofluid was numerically investigated for a wide range of relevant dimensionless numbers [27]. Numerical studies have revealed that the heat transfer performance of hematite containing ethylene glycol based nanofluids were better than hematite containing water based nanofluids [28]. The analyses of entropy generation in applications utilizing nanofluids have been reported [29–31], with higher entropy generation in copper-water nanofluid, in comparison with that in pure water [31]. The potential issue of nanofluids in biomedical application has driven several numerical investigations [32,33]. Accordingly, the modeling of peristaltic flow of copper-water nanofluid with carbon nanotubes has revealed the role of

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Nomenclature

C_p Specific heat (J/kgK)
D Diameter (m) of the test section
Gr Grashof number ($-$)
h Heat transfer coefficient (W/m^{2}K)
k Thermal conductivity (W/mK)
Nu Nusselt number ($-$)
Pr Prandtl number ($-$)
Q Amount of heat transferred (W)
T Temperature of test fluid ($^\circ$C)
V Volume of test fluid (m^3)

Greek symbols
ψ Shape factor or sphericity ($-$)
η Collection efficiency ($-$)
ϕ Nanoparticle volume fraction ($-$)
μ Viscosity (mPa.s)
θ Time (s)
ρ Density (kg/m^3)

Subscripts
NF   Nanofluid
PGW   Propylene glycol-water
r   Ratio

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nanoparticle volume fraction and Grashof number on pressure difference and temperature profile [32].

The wide variation in viscosity and thermal conductivity of nanofluids among reported literature for the same systems could be attributed to difference in nanoparticle size & shape and the different methods adopted for preparation of nanofluids [14,34–36]. While scaling the process of nanofluid preparation to higher volumes, reproducibility of characteristics of nanofluid prepared at different scales needs to be addressed. The cost of nanomaterial needs to borne in mind, while attempting real-time application of nanofluid.

Sand is a naturally available, low density material (density ~ 2.65 g/mL), comprising silica as its major component. Hence, with the use of sand as nanomaterial, the mass of nano-material required for preparation of 1 L of 2 vol % nanofluid can be brought down to 53 g. This is much lower when compared to the requirement (100–140 g for 1 L of 2 vol % nanofluid) of high density nanomaterial such as TiO$_2$, ZnO and CuO [22,37,38]. Sand-based nanofluids can be successfully prepared using top-down approach involving stirred bead milling and ultrasonication [37,39,40]. With very little cost for the raw material (naturally available sand as precursor for nanomaterial) and ease-of-scalability of stirred bead milling over a wide volume range, both the problems of nanomaterial cost and uncertainty in nanofluid characteristics can be overcome. We had reported the preparation and thermo-physical properties of nanoparticle dispersions of sand in different base fluids such as water, ethylene glycol-water and propylene glycol [39–41]. It is pertinent to note that in the last few years, interest among the research community to utilize sand as the precursor for nanomaterial preparation has increased, as evident from publications during this period [42,43].

This work is an attempt by us to utilize sand as precursor and stirred bead milling as the nanofluid preparation technique to prepare nanofluids with propylene glycol-water mixture (1:1 by volume) as the base fluid. The present work reports on the role of temperature and nanoparticle concentration on the viscosity and thermal conductivity of sand-propylene glycol (PG)-water nano-fluids. In addition, the potential of sand-PG-water nanofluid as heat transfer fluid has been assessed using a simulated plate solar collector. It is pertinent to note that only a very few detailed studies have been reported for nanofluids using propylene glycol-water as the base fluid.

2. Experimental

2.1. Stirred bead milling

Finely ground river-bed sand, passing through BSS350 (44 μm), was used as the precursor for preparation of nanofluids by stirred bead milling. The details of the stirred bead mill have been reported elsewhere [39]. During a typical experiment, about 60 g of sand was milled in 500 mL water using 1200 g of Yttrium stabilized zirconia beads in two stages, with beads of 0.5 mm and 0.2 mm used in the first and second stages respectively. The milling time for each stage was about 6 h for these operating conditions, as reported earlier. A concentrated nanoparticle suspension in water was obtained at the end of milling period, evaporation of which yielded sand nanoparticles.

2.2. Characterization of powders

The surface morphology of particles was studied using a field emission scanning electron microscope (JSM 6701F, JEOL, Japan). For this purpose, the particles were dispersed in acetone and drop cast on glass slide, which was subsequently mounted on a brass stub, before being imaged using scanning electron microscope. Gold was sputtered on the sample surface before imaging, to render its surface electrically conducting. The powder X-ray diffraction pattern was recorded using an X-ray diffractometer (D8 Focus, Bruker, Germany). The elemental composition of milled sand particles was determined using an X-ray fluorescence spectrometer (S8 Tiger, Bruker, Germany).

2.3. Preparation of nanofluid

Sand-propylene glycol nanofluid has been prepared by a two-step method reported in the literature [40]. Briefly, a concentrated sand-propylene glycol nanofluid was prepared, followed by dilution with equal volume of the water leading to sand-PG-water nanofluid containing equal proportion (by volume) of propylene glycol and water [44]. The required mass of sand nanoparticles was added to propylene glycol such that the nanoparticle volume concentration was 4%, followed by homogenization using a shear ho-mogenizer (Ultraturrax T25, IKA, Germany) and extended probe ultrasonication using a sonicator (Vibra-cell™, Sonics, USA). The sonicator was operated at 60% amplitude with the time for on-cycle and off-cycle being 45 s and 15 s respectively. The appropriate ultrasonication time required for satisfactory dispersion of sand nanoparticles was determined through periodic measurement of thermal conductivity and viscosity. The ultrasonication was stopped when there were no significant changes in thermal con-ductivity and viscosity between two time points. An equal volume of water was added to 4 vol % sand-propylene glycol dispersion, leading to 2 vol % sand-propylene glycol-water nanofluid.

2.4. Characterization of nanofluids

The hydrodynamic diameter, measured using dynamic light scattering, is widely employed to ascertain the state of aggregation of nanoparticles when dispersed in a liquid. A zetasizer (Nano ZS,