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Thermal performance of Al_2O_3 Nanoparticle Enhanced Ionic Liquids (NEILs) for Concentrated Solar Power (CSP) applications

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ABSTRACT

Nanoparticle Enhanced Ionic Liquids (NEILs) were synthesized by dispersing aluminum oxide (Al_2O_3) nanoparticles in 1-butyl-3-methylimidazolium bis{(trifluoromethyl)sulfonyl}imide, ($[C_4mim][NTf_2]$) ionic liquids (ILs). The experimental assessment of NEILs includes investigating the effective thermo-physical properties and forced convection heat transfer under laminar and turbulent flow regime. The results show that thermal conductivity and heat capacity enhanced up to ~11% and ~49% respectively for 0.9 vol% NEILs. The rheological behavior of NEILs shows non-Newtonian shear thinning behavior with shear viscosity decreasing with increasing shear rate. The viscosity of NEILs shows much higher value compared to the base ILs for a small amount of nanoparticles dispersion and also has a strong temperature dependency. Measured viscosity and thermal conductivity were found to be much higher than predicted by the well-established model for dilute suspensions. The convective heat transfer performance increases with the nanoparticles concentration within the measured nanoparticles vol%; up to ~27% and ~40% enhancement in heat transfer coefficient was found in laminar and turbulent flow regime respectively. The possible mechanisms of the enhanced thermal performance are discussed.

1. Introduction

The energy crisis is one of the most important issues in the recent global world. Everyone is looking for pollution free alternate energy sources. Concentrated Solar Power (CSP) is one of the developing alternative energy technology, where mirrors or lenses are used to concentrate sunlight from a large area and are stored in a collector filled with heat transfer fluid (HTF) [1]. Later on the energy of those HTF is used to produce steam for power generation. Commonly used HTF such as Therminol VP-1 (eutectic mixture of biphenyl and diphenyl oxide), thermal oil, and molten salt [2] have low decomposition temperature and high melting point, which are affecting the energy storage capacity and reducing the overall system efficiency, resulting in an increase of the operating cost. Therefore, there is an acute need for the new energy-efficient HTF.

Ionic liquids (ILs) are a class of molten salt, which has melting point below 100 °C, high thermal stability, and negligible vapor pressure [3]. These properties make them as a potential candidate for CSP applications over the currently used HTF [4]. The negligible vapor pressure and high thermal stability simplify the heat transfer and heat storage system [5]. In addition, nanofluids, which are defined as dispersion of metallic (Cu, Ag, and Au) or nonmetallic (Al_2O_3, CuO, TiO_2) particles with one dimension less than 100 nm in a base liquid [6], have great attraction due to their enhanced thermophysical properties and enhanced thermal performance [7–11]. Water and ethylene glycol based nanofluids already show their potential applicability as cooling media for high heat generating electronic device, nuclear plant, automobile industry [12,13]. These enhanced heat transfer properties of nanofluids encourage the researchers to combine these two (nanoparticles and ionic liquids) growing interests, forming the Nanoparticle Enhanced Ionic Liquids (NEILs) by dispersing small amounts of nanoparticles into base ILs. The practical applications of NEILs are as heat transfer fluids; and can be used for heat exchange in chemical plants, absorption cooling cycle systems, and solar thermal power generation [14,15]. Thermophysical properties of the ILs based nanofluids were studied by several researchers [14–17]. Nieto de Castro et al. [14,15] studied several imidazolium and pyrrolidinium ILs based nanofluids and reported ~9% thermal conductivity enhancement for 0.01 mass fraction of multi wall carbon nanotubes (MWCNTs) and ~8% heat capacity enhancement for 0.01 and 0.015 mass fraction of Baytubes. Enhanced thermal

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Nomenclature

q''	heat flux [W/m^2]
Q	input power [Watt]
V	voltage [Volt]
I	current [amp]
A_h	heating surface area [m^2]
T	temperature [°C]
x	axial distance [m]
k	thermal conductivity [W/m K]
D_o	tube outer diameter [m]
L	heating length of test section [m]
$h(x)$	local heat transfer coefficient [W/m^2 K]
r	tube radius [m]
c_p	heat capacity [J/g K]
V'	volumetric flow rate [m^3/s]
f	friction factor [~]

Greek symbols

ϕ	nanoparticles volume fraction [~]
μ	dynamic viscosity [kg/s m]
α	thermal diffusivity [m^2/s]
ν_f	kinematic viscosity [m^2/s]
ρ	liquid density [kg/m^3]

Subscripts

NEIL	nanoparticle enhanced ionic liquid
BL	base liquid
n	nanoparticle
f	fluid
w	wall
i	inner
s	steel
h	hydrodynamic
t	thermal

conductivity and lower heat capacity of ILs based nanofluids containing graphene (GE) and MWCNTs nanoparticles was observed by Wang et al. [16]. Paul et al. [17] have recently reported the ~23% enhancement of heat capacity of NEILs made with N-butyl-N-methylpyrrolidinium bis{(trifluoromethyl)sulfonyl}imide ([C_4mpyrr][NTf_2]) IL and 1 wt% Al_2O_3 nanoparticles. Shin et al. [18] reported enhanced heat capacity of nanofluids synthesized by lithium carbonate and potassium carbonate (62:38 ratio) and alkali chloride salt eutectic with SiO_2 nanoparticles (1% by wt.) for solar thermal applications. Although there are several previous studies on thermal properties and the stability of the NEILs, none of these studies report heat transfer behavior of NEILs. The heat transfer behavior of NEILs will play an important role in assessing its effectiveness and viability of CSP applications.

In the present study, forced convection experiments were carried out in a circular tube with an inner diameter of 3.86 mm in the laminar and turbulent flow regime for NEILs. NEILs was synthesized with 1-butyl-3-methylimidazolium bis{(trifluoromethyl)sulfonyl}imide ([C_4mim][NTf_2]) and 0.18, 0.36, and 0.9 vol% Al_2O_3 nanoparticles. Thermophysical properties of NEILs were also measured and compared with base IL. Findings from these experiments will be very important for assessing the performance of NEILs in solar collector applications.

2. Experimental methods

2.1. Synthesis of NEILs

0.18%, 0.36%, and 0.9% (volume%) NEILs were prepared by 1-butyl-3-methylimidazolium bis{(trifluoromethyl)sulfonyl}imide, ([C_4mim][NTf_2]) IL with Al_2O_3 nanoparticles. 99% pure [C_4mim][NTf_2] IL was purchased from IoLiTec Company (Germany). Molecular weight of [C_4mim][NTf_2] is 419.37 g/mol. The chemical structure of the anion, cation of IL is shown in Fig. 1.

Molecular formula: $C_{10}H_{15}F_6N_3O_4S_2$

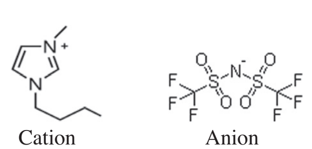

Fig. 1. Chemical structure of cation and anion of [C_4mim][NTf_2] IL.

Aluminum oxide (Al_2O_3) nanoparticles was dispersed in the base IL by using vortex mixture. NEILs were processed for around 90 min in the votexture to break possible aggregations of nanoparticles. Al_2O_3 nanoparticles was purchased from Sigma–Aldrich, USA. Al_2O_3 nanoparticles are γ-phase with particle size <50 nm (TEM), and the surface area >40 m^2/g (BET). SEM image of the Al_2O_3 nanoparticles and TEM image of 0.18 vol% NEILs is presented in Fig. 2(a) and (b) respectively.

2.2. Thermophysical property measurements

The density of base IL and NEILs were measured by a Pycnometer (Thomas Scientific). The Pycnometer was 1 mL in size. The empty Pycnometer and sample filled Pycnometer was weighing by using METTLER TOLEDO balance which has a precision of 0.01 mg. Density was determined by those weight difference. The Pycnometer and the samples were placed in a thermal bath (Thermo NESLAB) to maintain a uniform temperature. Before using for IL and NEILs the Pycnometer was calibrated with water.

The viscosity of base IL and NEILs were measured by using a cone and plate type rotary viscometer (LVDV-II+ProCP, from Brookfield Engineering Co.). The sample size of the cone and plate arrangement is 1 mL. The cone and plate arrangement has a thermal jacket to maintain a constant sample temperature and it has the temperature accuracy within ±0.1 °C. A thermal bath (Thermo NESLAB) was used to maintain constant temperature of the measuring sample. Temperature accuracy of the bath was within ±0.01 °C. The viscometer was calibrated by using company standard liquid.

Thermal conductivity of base IL and NEILs were measured by using the KD2 Pro thermal property analyzer (Decagon Device, USA). The measurement principle is based on the transient hot wire method. The meter has a probe with 60 mm length and 1.3 mm diameter with a heating element and a thermoresistor, which is inserted vertically into the test sample. The probe is connected to a microcontroller for controlling and conducting the measurements. Before using for IL and NEILs, the meter was calibrated with distilled water and standard glycerin. Thermal bath (Thermo NESLAB) was used to maintain a constant temperature of the measuring sample.

The heat capacity of base IL and NEILs were measured using Differential Scanning Calorimetry (DSC Q2000 from TA instruments Inc.). The sample was placed in a standard aluminum hermetic pan