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Thermal performance of ionic liquids for solar thermal applications

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ABSTRACT

Experimental investigations were carried out to evaluate thermophysical properties, i.e. density, viscosity, heat capacity, and thermal conductivity and high temperature forced convection behavior of N-butyl-N,N,N-trimetylammoniumbis(trifluormethylsulfonyl)imide ($[N_{4111}][NTf_2]$) ionic liquid (IL) for its potential application in concentrated solar power (CSP). Results from the experiments will be useful in assessing the potential of using ILs for solar thermal collectors. Experimental results show that thethermal conductivity was slightly decrease with the increase of temperature; vary from 0.124 to 0.121 W/m K for a change in temperature of 283–343 K, strong temperature effect on the viscosity of IL was observed and maintain an exponential relationship with the temperature; heat capacity increases linearly with temperature measured from 298 to 618 K. Forced convection performance of the IL was studied in a circular tube under both in laminar and turbulent conditions. Although the heat transfer coefficient of the IL was found to be lower compared to the De-Ionized (DI) water, its thermal stability and other attractive properties may make it a viable candidate for solar collector use. Our experimental results also established that Shah's equation and Gnielinski's equation can predict forced convection performance of IL for both the laminar region and turbulent region respectively.

1. Introduction

Concentrating sunlight from a large area using mirrors or lenses is an effective means to utilize solar energy and potentially an inexpensive means to replace conventional natural gas or coal to produce steam for electricity generation [1]. In concentrating solar power (CSP) plants, solar energy is concentrated using mirrors and lenses and stored in a fluid; this stored energy is transferred to generate steam for electrical power generation. Working fluid used in the CSP plant plays the vital role and determines the overall efficiency of the system. Currently used working fluid have low to moderate thermal stability and low heat storage capacities that results in high operating costs [2], which necessitates the development of new energy-efficient working fluids. Energy-efficient working fluid should have high temperature thermal stability and high energy storage capability.

Ionic liquids (ILs)-a group of salts, which are liquid at ambient temperature (less than 100 °C) and are considered as the potential replacement of the currently used working fluid [3–8]. ILs have several excellent physical and chemical properties including high thermal stability, negligible vapor pressure and volatility, exposure to air and moisture stability, low melting point, wide electrochemical window, nonflammability, high ionic conductivities, high solvating capability, corrosion resistance to plastics and carbon steels [9–18]. For those excellent properties, ILs become very useful in material processing [19], as a catalyst for synthesis of inorganic nano-materials [20], and as lubricants [21].

Due to its diverse potential applications, ILs are being investigated by a number of researchers to explore different perspective of the liquid; most of these researches have concentrated on the study of thermophysical properties; among those only a few numbers of study were concentrated on the study of thermal and transport properties [22–27]. To the best of the authors, no study has been reported yet on high temperature and turbulent heat transfer performance of this ILs. To assess effectiveness of ILs in CSP plants, conjugate study of thermophysical properties and high temperature heat transfer performance is necessary.

Here, we are reporting results of our experimental study on thermophysical property measurement and high temperature convective heat transfer study. N-butyl-N,N,N-trimetylammonium-bis(trifluormethylsulfonyl)imide ($[N_{4111}][NTf_2]$) are chosen as the ionic liquid to study as it is the most common, commercially available and previously studied ionic liquid for thermophysical property, i.e. density, viscosity, thermal conductivity and heat capacity [27]. Heat capacity and thermal conductivity have been

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Nomenclature

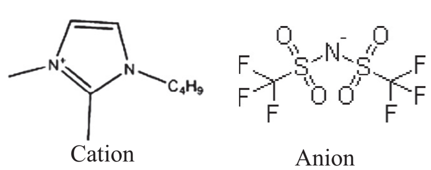
q''	heat flux (W/m^2)
Q	input power (W)
V	voltage (Volt)
I	current (amp)
A_h	heating surface area (m^2)
T	temperature (°C)
x	axial distance (m)
k	thermal conductivity (W/m K)
D_o	pipe outer diameter (m)
L	heating length of test section (m)
$h(x)$	local heat transfer coefficient (W/m^2 K)
r	pipe radius (m)
c_p	heat capacity (J/g.K)
V'	volumetric flow rate (m^3/s)
f	friction factor (∼)
Greek symbols	
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	
f	fluid
w	wall
i	inner
s	stainless steel

previously studied by Liu et al. [27] for the temperature range of 343–450 K and 284–314 K respectively. In our study, we conducted heat capacity, viscosity and thermal conductivity measurement in the range of 298–618 K, 293–363 K, and 283–343 K respectively along with forced convection study in a circular pipe in both laminar and turbulent regions. Heat capacity will indicate energy storage capacity of the ILs in CSP system, viscosity will indicate pumping power penalty for the ILs, thermal conductivity and forced convection performance indicate its performance in the secondary heat exchanger. The results of this report are important for the comprehensive assessment of this ionic liquid and potential application in CSP plant.

2. Experimental

2.1. Ionic liquid

99% Pure N-butyl-N,N,N-trimetylammoniumbis(trifluormethyl sulfonyl)imide ([N_{4111}][NTf_2]) IL was purchased from IoLiTec Company, Germany. CAS (Chemical Abstracts Service) registry number is 258273-75-5. Molecular weight of [N_{4111}][NTf_2] is 396.37 g/mol. The chemical structure of the anion and cation and the molecular formula of the ionic liquid are as follows:



Molecular formula: $C_9H_{18}F_6N_2O_4S_2$

2.2. Thermophysical property measurement

The density of ionic liquid was measured using a 1 mL Pycnometer from Thomas Scientific. The pycnometer and the sample were placed in a thermal bath (Thermo NESLAB) to maintain a constant temperature. The weight of the sample was measured by METTLER TOLEDO balance, which has a precision of 0.01 mg. Before using for IL, the pycnometer was calibrated with water. The density measurements were repeated at least three times at each temperature and the standard deviation of the measurement was ±0.84%.

The viscosity of the ionic liquid was measured 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 using standard liquid (company provided). For each temperature three measurements were taken and the measurement standard deviation was estimated to be ±3.2%.

The heat capacity of the ionic liquid was measured using Differential Scanning Calorimetry (DSC Q2000 from TA instruments Inc.). The sample was placed in a standard aluminum hermetic pan covered with lid and the average sample size was 16.35 mg. Nitrogen was used as the cooling system at a flow rate of 40 mL/min. The DSC run was performed from 298.15 to 618.15 K at a heating rate of 10 °C/min.

Thermal conductivity of the ionic liquid was measured by using the KD2 Pro thermal property analyzer (Decagon Device, USA). Measurement principle of this device 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, 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. For each measurement at least five readings were

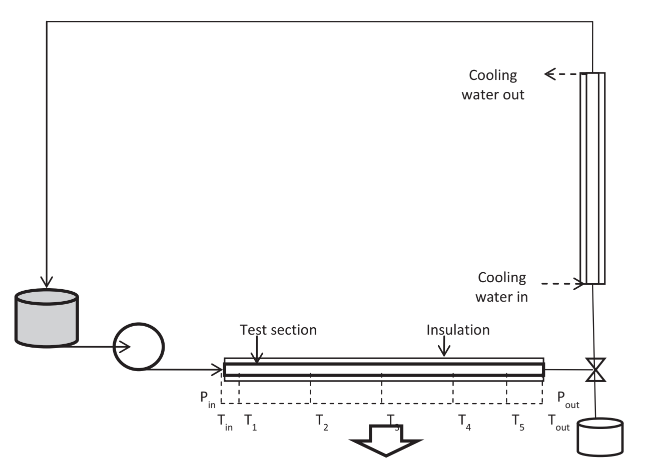


Fig. 1. Schematic of forced convection study loop.