Thermal performance of Al₂O₃ 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 (Al₂O₃) nanoparticles in 1-butyl-3-methylimidazolium bis{(trifluoromethyl)sulfonyl}imide, ([C₄mim][NTf₂]) ionic liquids (ILs). The experimental assessment of NEILs includes investigating the effective thermophysical 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.

Keywords: Nanoparticle Enhanced Ionic Liquids (NEILs); Effective thermal conductivity; Rheological behavior; Forced convection; Heat transfer coefficient; Laminar flow; Turbulent flow

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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 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 ([C₄mpyrr][NTf₂]) IL and 1 wt% Al₂O₃ 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 SiO₂ 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 ([C₄mim][NTf₂]) and 0.18, 0.36, and 0.9 vol% Al₂O₃ 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.

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

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

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, ([C₄mim][NTf₂]) IL with Al₂O₃ nanoparticles. 99% pure [C₄mim][NTf₂] IL was purchased from IoLiTec Company (Germany). Molecular weight of [C₄mim][NTf₂] is 419.37 g/mol. The chemical structure of the anion, cation of IL is shown in Fig.1.

Molecular formula: C₁₀H₁₅F₆N₃O₄S₂

Aluminum oxide (Al_2O_3) nanoparticles were dispersed in the base IL by using vortex mixture. NEILs were processed for around 90 min in the vortex to break possible aggregations of nanoparticles. Al_2O_3 nanoparticles were purchased from Sigma-Aldrich, USA. Al_2O_3 nanoparticles are γ -phase with particle size $< 50\text{nm}$ (TEM), and the surface area $>40\text{ m}^2/\text{g}$ (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 were weighed 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 $\pm 0.1^\circ\text{C}$. A thermal bath (Thermo NESLAB) was used to maintain constant temperature of the measuring sample. Temperature accuracy of the bath was within $\pm 0.01^\circ\text{C}$. 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 covered with lid. Nitrogen was used as cooling system at flow rate of 40 mL/min. The DSC run was performed from 25°C to 345°C at a heating rate of 10°C/min.

2.3. Heat transfer coefficient measurements

2.3.1. Experimental setup

Fig. 3 presents the schematic of the flow loop used in thermal performance of NEILs experiment. The loop consists of a pump, test section, heat exchanger, collection tank, and pressure transducer. The pump was connected to a frequency inverter which was calibrated for the pump using a stopwatch and bucket method. The test section was a stainless steel tube of 3.86 mm inner diameter, 6.35 mm outer diameter, and 990.6 mm length. Uniform heat flux was applied to the test section using a flexible heating tape (OMEGA Engg. FGS101-040). Power was supplied to the heater using a DC power (Agilent Technologies: 6655A) supply. To reduce the heat loss to the ambient and ensure constant heat flux condition, the entire test section was insulated with fiberglass insulation. Five thermocouples were mounted on the tube surface to measure the surface temperature. The thermocouples position was at a normalized axial distance with respect to the tube diameter (x/D) of 23.03 (T_1), 75.65 (T_2), 128.28 (T_3), 180.92 (T_4), and 233.55 (T_5) from the test section inlet. Another two thermocouples were inserted into the tube to measure the inlet and outlet liquid bulk temperatures. A differential pressure transducer was connected between the inlet and outlet of the test section to measure the pressure drop within the test section. All thermocouples and the pressure transducer were connected to a National Instrument (NI) data acquisition system cDAQ-9178 via a temperature card NI 9211 and pressure card NI 9203 which were interfaced with a computer. Labview software was used for recording all data.

2.3.2. Experimental procedure

To perform the experiment with base IL and NEILs, the whole test loop was washed out with DI-water and run the pump for several hours to remove all water bubbles from the test loop. After that, the experimental liquid was placed in the tank and the pump was set to run at a desired flow rate. At the same time, the desired power input from the DC power supply was applied. The test section was allowed to reach steady state before the temperature data was recorded, which was

monitored by the LabView software. After recording the data, the next pump flow rate was increased and repeats the same procedure up to maximum allowable flow rate of the pump.

2.3.3. Data processing

Heat flux (q'') was calculated from input power (Q) of the heater and heating surface area (A_h) using the following equation:

$$q'' = \frac{Q}{A_h} = \frac{VI}{\pi D_o L} \quad (1)$$

where V and I are the input voltage and current respectively, D_o is the outer diameter of tube, and L is the heating length.

Local heat transfer coefficient at an axial distance x , along the test section, $h(x)$, was calculated using the equation:

$$h(x) = \frac{q''}{T'_w(x) - T_f(x)} \quad (2)$$

where $T'_w(x)$ and $T_f(x)$ are the local temperatures of the inner surface and liquid respectively.

The inner surface temperature was calculated using steady state one-dimensional heat conduction equation with constant heat flux boundary condition for which the governing equation is [19]:

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) = 0 \quad (3)$$

The solution for the inner surface temperature becomes

$$T'_w(x) = T_w(x) - \frac{Q \cdot \ln(r_o/r_i)}{2\pi L k_s} \quad (4)$$

where $T_w(x)$ is the local temperature of outer surface as measured by the thermocouples, r_o and r_i are the outer and inner radius of the test tube respectively, and k_s is the thermal conductivity of stainless steel.

Meanwhile, local temperature of the liquid was calculated using the energy balance relation:

$$T_f(x) = T_{fi} + \frac{Q}{\rho C_p V'} \frac{x}{L} \quad (5)$$

where T_{fi} is the liquid inlet temperature of the test section, C_p is the heat capacity of the liquid, and V' is the volumetric flow rate. All the fluid properties were evaluated at the average ($T_{av} = \frac{T_{in} + T_{out}}{2}$) of the inlet and outlet fluid temperature of the test section.

2.4. Uncertainty and error analysis

The measurement uncertainty of thermocouples, voltage, and current are $\pm 0.18^\circ\text{C}$, $\pm 0.01\text{V}$, and $\pm 0.001\text{A}$ respectively. A systematic uncertainty analysis was performed using standard Kline and McClintock method [20].

$$W_p = \sqrt{\sum_{i=1}^n \left(\frac{\partial p}{\partial a_i} w_i \right)^2} \quad (6)$$

where, W_p is the total uncertainty of calculating parameter, p , and a_i variables of functional dependence, and w_i is the uncertainty of the independent variables. Input power uncertainty was calculated $\pm 0.15\%$, heat transfer coefficient has an uncertainty of $\pm 0.89\%$. Since the dimensionless numbers are the functions of numerous measured quantities and physical properties, therefore, the uncertainty will propagate. The uncertainties associated with the Nusselt number and Reynolds number were calculated $\pm 4.35\%$ and $\pm 5.86\%$ respectively.

3. Results and discussion

3.1. Density of NEILs

The temperature dependent density of base IL and NEILs (0.18, 0.36, and 0.9 vol%) are presented in Fig. 4 and it is clear that density of base IL and NEILs decreases with temperature within the measured temperature 10-70°C. NEILs shows higher density compared to the base IL and density increases with nanoparticles concentration in a particular temperature. It is obvious that the higher density of NEILs is the results of mixing of high density Al_2O_3 nanoparticles. The density data were used for forced convection heat transfer parameter calculations.

3.2. Rheological behavior of NEILs

Rheological behavior of base IL and NEILs (0.18, 0.36, and 0.9 vol%) were measured within the temperature range 20-90°C. Fig. 5(a) shows the rheological behavior of three concentrations of NEILs at 25°C. It can be seen that the viscosity decreases with increasing shear rate, which indicates a shear thinning behavior and 0.9 vol% NEILs shows stronger shear thinning behavior than lower concentration because at higher concentration the nanoparticles agglomeration also increases that increases the viscosity at a certain shear rate. The effective shear viscosity of NEILs at 25°C was present as a function of nanoparticle concentration in Fig. 5(b) and the experimental data was compared with the Batchelor equation [21] for dilute non-interacting suspensions of spherical particles.

$$\frac{\mu_{NEIL}}{\mu_{BL}} = 6.2\phi^2 + 2.5\phi + 1 \quad (7)$$

where μ_{NEIL} and μ_{BL} are the viscosity of NEILs and base liquid, ϕ is the nanoparticle volume fraction. The relative shear viscosity and nanoparticle concentration relation is non-linear. It can be seen from the Fig. 5(b) that NEILs at concentration below 0.18 vol% agree well with the model but the model could not predict the effective viscosity of NEILs for 0.36 vol% and 0.9 vol%. The predicted effective shear viscosity of NEILs was lower than the experimental measured values because the model only considered the viscosity of base IL and nanoparticle concentration and it does not consider the nanoparticles agglomeration in ILs. But the experimental enhancements of shear viscosity values are consistent with the previously published literature [22-23] where NEILs were synthesized with base IL and Al₂O₃ nanoparticles and functionalized multi-walled carbon nanotubes (F-MWCNTs). Using least-square curve fitting, the present experimental shear viscosity data of NEILs can correlate with the volumetric particle concentration in a form of ($R^2 = 0.99$):

$$\frac{\mu_{NEIL}}{\mu_{BL}} = 19088\phi^2 + 3.733\phi + 1 \quad (8)$$

Fig. 5(c) shows the shear viscosity of base IL and 0.18, 0.36, and 0.9 vol% NEILs as a function of temperature and indicates strong temperature effect on base IL and NEILs. Fig. 5(d) shows the shear viscosity 0.9 vol% NEILs as a function of shear rate at different temperature. The shear thinning behavior occurs at all the measured temperatures and the shear thinning

increases with the temperature. Fig. 5(e) represents the viscosity of 0.36 vol% NEILs at different time and temperature and it is clear that viscosity does not change within that period.

3.3. Effective thermal conductivity of NEILs

Fig. 6(a) shows the effective thermal conductivity of NEILs as a function of temperature. It is clear from the Fig.6(a) that the thermal conductivity increases with the vol% of nanoparticles over the measured temperature range and slightly increasing thermal conductivity enhancement with temperature was observed. The maximum enhancement was observed ~11% for 0.9 vol% NEILs. At a certain temperature, the normalized thermal conductivity enhancement with nanoparticle concentration was presented in Fig. 6(b). In Fig. 6(b) also shows the comparison of normalized thermal conductivity between experimental measurements and predicted effective thermal conductivity by well established Maxwell [24] equation.

$$\frac{k_{NEIL}}{k_{BL}} = \frac{k_n + 2k_{BL} - 2\phi(k_{BL} - k_n)}{k_n + 2k_{BL} + \phi(k_{BL} - k_n)} \quad (9)$$

where k_{NEIL} , k_{BL} , $k_n = 36 \text{ W/mK}$ are the thermal conductivity of NEIL, base IL, and Al_2O_3 nanoparticles respectively. ϕ is the nanoparticle volume fraction. The mechanism of thermal conductivity enhancement of traditional nanofluids had been discussed by numerous researchers. The possible mechanism includes the Brownian motion of nanoparticles, liquid layering in liquid/nanoparticle surface interface, the nature of heat transport to the nanoparticles, and the effect of nanoparticle clustering and structuring [7,25-26].

From the Fig. 6(b), it is clear that the predicted effective thermal conductivity of NEILs was much lower than the experimental measured values. That is because of the same as viscosity model, the model only considers the thermal conductivity of particles, base liquid, and nanoparticle volume fraction. The exact mechanism of thermal conductivity enhancement of NEILs is unclear. Nieto de Castro et al. [14-15] predicted their experimental values by considering the interfacial layer model and found well prediction with 2 nm interfacial layer thickness. Our experimental enhancements of NEILs were consistent with the literature [14-15, 22] where they synthesize the NEILs with base ILs Al_2O_3 and multi wall carbon nanotubes (MWCNTs). The present experimental thermal conductivity data of NEILs can correlate with the

volumetric particle concentration by using least-square curve fitting and the form of the equation is ($R^2 = 0.99$):

$$\frac{K_{NEIL}}{K_{BL}} = 12.496\phi + 1 \quad (10)$$

Fig. 6(c) represents the thermal conductivity of 0.36 vol% NEILs at different time and temperature and it is clear that thermal conductivity does not change within that period.

3.4. Heat capacity of NEILs

The heat capacity of base IL and 0.18, 0.36, and 0.9 vol% NEILs over 25-345°C with an interval of 10°C are presented in Fig. 7. The heat capacity of base IL and NEILs increases almost linearly with temperature. Heat capacity of NEILs shows much higher value compared to the base IL and average 16%, 30%, and 49% enhancement was observed for 0.18, 0.36, 0.9 vol% NEILs respectively. The significant enhancement in heat capacity of NEILs was observed by Nieto de Castro et al. [14-15] where the IoNanofluids were synthesis with $[C_4mim][PF_6]$ IL and 1 wt% multi wall carbon nanotubes (MWCNTs). The present temperature dependent heat capacity data were used to calculate the forced convection parameters.

3.3. Convective heat transfer coefficient

3.3.1. Convective heat transfer coefficient of DI water

Before doing the experiments with base IL and NEILs, the experimental system was tested with DI-water to evaluate the reliability of measurements. Fig. 8(a) and (b) shows the heat transfer behavior of DI-water with the axial distance at laminar ($Re < 2300$) and turbulent ($Re > 2300$) flow region. The experimental results were compared with the well known Shah's correlation for laminar flow [27] and Gnielinski's equation for turbulent flow [28] at the constant heat flux boundary conditions:

$$Nu(x) = \begin{cases} 1.953 \left(RePr \frac{D}{x} \right)^{\frac{1}{3}} & (RePr \frac{D}{x}) \geq 33.3 \\ 4.364 + 0.0722 RePr \frac{D}{x} & (RePr \frac{D}{x}) < 33.3 \end{cases} \quad (11)$$

Gnielinski's equation for turbulent flow is at a range of $0.5 < Pr < 10^6$ and $2300 < Re < 5 \times 10^6$:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re-1000)Pr}{1.07 + 12.7\sqrt{\frac{f}{8}(Pr^{\frac{2}{3}}-1)}} \quad (12)$$

where $Nu(x)$, Re , Pr are the local Nusselt number, Reynolds number, and the Prandtl number respectively and defined as:

$$Nu(x) = \frac{h(x)D}{k_f} \quad Re = \frac{\rho u D}{\mu} \quad Pr = \frac{\nu_f}{\alpha} \quad (13)$$

where D is the inner diameter of test section, k_f is the thermal conductivity of fluid, ρ is the fluid density, μ is the fluid viscosity, u is the fluid velocity, $\nu_f (= \frac{\mu}{\rho})$ is the fluid kinematic viscosity, and $\alpha (= \frac{k_f}{\rho c_p})$ is the fluid thermal diffusivity and f is the friction factor, which was calculated by:

$$f = \frac{1}{\{1.82 \log_{10}(Re) - 1.64\}^2} \quad (14)$$

It is clear from Fig. 8(a) and 8(b) that there are reasonably good agreements between the predicted and measured heat transfer coefficient DI-water over the Reynolds number range studied for laminar and turbulent flow regime.

3.3.2. Convective heat transfer coefficient of NEILs

After getting confidence in the experimental system, forced convection experiments were performed for base IL and NEILs in laminar and turbulent flow condition. Fig. 9 presents the typical temperature profile of the fluid and tube surface of the test section along the axial distance and it shows increasing fluid temperature with axial distance because of constant wall heat flux condition.

The local heat transfer coefficient of base IL and NEILs as a function of axial distance at laminar ($Re = 1500 \pm 50$) and turbulent ($Re = 4500 \pm 50$) flow regimes are presented in Fig.10(a) and (b). Due to the viscosity variation of base IL and NEILs, the maximum variation in Reynolds number was occurred ± 50 . Because of the much higher shear viscosity of 0.9 vol% NEILs, turbulent flow could not be achieved. It is clear from Fig. 10(a) and (b) that the NEILs

has significantly higher heat transfer coefficient than base IL and higher concentration NEILs has more enhancement. As of Fig. 10(a) at point 2 ($x/D=75.65$), the enhancement of heat transfer coefficients are ~15%, 28%, and 31% for 0.18, 0.36, and 0.9 vol% NEILs respectively. For turbulent flow in Fig. 10(b) at point 2 ($x/D=75.65$), the enhancement of heat transfer coefficients are ~26% and 29% for 0.18 and 0.36 vol% NEILs respectively. At a certain concentration of NEILs in the laminar flow regime, the enhancement of heat transfer coefficient is more in the entrance region; for example, 0.36 vol% NEILs the enhancement of heat transfer coefficient is varied from 27.5% ($x/D=23.02$) to 16.4% ($x/D=233.55$). But in the turbulent regime, the enhancement of heat transfer coefficient does not follow any imperative rule with the axial distance. The higher enhancement was observed in the turbulent flow regime compared to the laminar flow regime. For example, at $Re = 4500$ the average heat transfer enhancement of 1 wt% NEILs is ~31% and at $Re = 1500$ the average heat transfer enhancement of same concentration NEILs is ~19%. The heat transfer enhancement rate is not linear with the concentration of nanoparticles. The enhancement of 0.18 vol% and 0.36 vol% NEILs shows almost the same rate of enhancement but at 0.9 vol% NEILs, it does not enhance too much compared to the 0.18 and 0.36 vol% NEILs. At a certain concentration and Reynolds number in the laminar regime, the heat transfer coefficient decreases with the axial distance which is clear in Fig. 10(a). This is because of the entrance effect; initially the boundary layer thickness is lower and after the fully developed boundary layer the heat transfer coefficient becomes constant.

The enhancement of heat transfer coefficient was also reported by other researchers, in where forced convection experiments were carried out for Al_2O_3 -water nanofluids at laminar [8-10] and turbulent [11] flow regimes. Wen et al. [8] reported up to ~47% enhanced heat transfer of 1.6 vol% Al_2O_3 -water nanofluids. Lai et al. [9] investigated forced convection of Al_2O_3 -water nanofluids in a 1.02 mm diameter tube and reported enhanced heat transfer coefficient of nanofluids. Heris et al. [10] reported enhanced heat transfer coefficient of Al_2O_3 -water nanofluids performing forced convection in a circular tube with the constant temperature boundary condition. Torii [11] studied the forced convection of diamond, CuO, and Al_2O_3 nanofluids in the turbulent flow regime and reported 9.8%, 6.6%, and 5.4% enhancement of the Nusselt number respectively for 1 vol% nanofluids at $Re = 6000 \pm 100$.

The present experimental enhancements of convective heat transfer coefficient depending on the nanoparticle concentration, Reynolds number, and axial distance are not fully reliant on the thermal conductivity enhancement. In an example, the maximum thermal conductivity enhancement of 0.9 vol% NEIL was found ~11% which is much less than the convective heat transfer enhancement at the same concentration. The local convective heat transfer coefficient h can be defined approximately k_{NEIL}/δ_t , where δ_t is the thermal boundary layer thickness [19]. It is clear from the correlation of heat transfer coefficient that the enhanced heat transfer coefficient of NEILs depends on either the thermal conductivity enhancement or the decrease in thermal boundary layers. One of these reasons may be the dynamic effect of the thermal conductivity. The experimental local heat transfer coefficients are measured based on the static thermal conductivity measurements from Fig. 6(a). But in the flow condition through a circular pipe, significant shear exists in the NEILs. NEILs also shows shear thinning behavior which may be the results of higher effective thermal conductivity of NEILs at flow conditions compared to the static conditions. The enhanced thermal conductivity at dynamic conditions was observed by Ahuja [29] for saline/polystyrene latex suspension who reported that enhancement of thermal conduction was followed by the particle rotation. Shin et al. [30] also measured the effective thermal conductivity of micro-particles suspended at rotating coquette flow conditions and found enhanced thermal conductivity.

In the circular pipe flow, the flow became hydrodynamically and thermally developed at $(x/D)_h \geq (0.05.Re)$ and $(x/D)_t \geq (0.05.Re.Pr)$ respectively [19]. In the present experiment, the flow is not thermally developed because of high Prandtl number of IL and NEILs. The inclusion of nanoparticles affects the boundary layer development as well as the heat transfer coefficient. NEILs has greater thermal developing length compared to base IL and it increases with the nanoparticles concentration that is clear in Fig. 10(a). The higher thermal developing length of NEILs means smaller thermal boundary layer thickness at a certain location which may lead to the enhanced heat transfer coefficient of NEILs. Particle migration, viscosity, and shear rate gradient may also have an effect on the boundary layer development [31-32]. In this mechanism, particles have the tendency to concentrate in the center of the pipe which leads to the decrease in viscosity near the wall as well as lower boundary layer thickness. Ding et al. [31] and Wen [32] formulated a theoretical model to observe the particle migration flowing through

the circular pipe and minichannels respectively and reported non-uniformity in particle concentration, which has consequence in higher heat transfer. Based on the shear thinning behavior of NEILs as shown in Fig. 5(a), the enhanced heat transfer coefficient of NEILs also maybe the result of particle migration in flow conditions. Aggregation of nanoparticles in base liquid is a common phenomenon that increases the effective thermal conductivity [33] and leads to the enhancement of heat transfer coefficient. In Fig. 2(b), the TEM image of NEILs shows aggregation of primary particles which also promising to higher heat transfer.

The previous studies of flow and possible mechanism of the enhancements are based on the traditional nanofluids. But the exact mechanism for enhanced heat transfer coefficient of NEILs is unclear. Pensado et al. [34] performed molecular dynamic simulations for salvation and stabilization of nanofluids containing ruthenium nanoparticle in ILs and reported that nanoparticles are in contact with the anion and cation of ILs. Carper et al. [35] theoretically modeled IL and Al_2O_3 surfaces and reported complex interaction formation of IL with Al–O surface. The high-quality contact of the IL with nanoparticles may be another plausible reason for the thermal conductivity and heat transfer coefficient enhancement in flow conditions [36].

Fig. 11(a) and (b) shows the heat transfer coefficient base IL and NEILs as a function of Reynolds number at laminar and turbulent flow regime respectively at $x/D=75.65$. In both cases, the heat transfer coefficient increases with the Reynolds number. This observation could be explained by the boundary layer thickness. At high Reynolds number, boundary layer becomes thinner and shear stress increases within the boundary layer. This alters the migration behavior of the nanoparticles, which in turn increases the heat transfer coefficient. The heat transfer enhancement with nanoparticle concentration is also clear from the Fig. 11(a) and (b).

4. Conclusions

Systematic forced convection experiments were performed for the Al_2O_3 Nanoparticle Enhanced (0.18, 0.36, and 0.9vol%) 1-butyl-3-methylimidazolium bis{(trifluoromethyl) sulfonyl}imide ($[\text{C}_4\text{mim}][\text{NTf}_2]$) Ionic Liquids (NEILs). Thermophysical properties of NEILs were measured experimentally. From the experimental results, the following conclusions can be drawn:

-NEILs shows shear thinning behavior with decreased shear viscosity at increasing shear rate. Shear thinning behavior occurs at all measured temperatures and increases shear thinning behavior with temperature. Shear viscosity of NEILs was enhanced with nanoparticle concentration compared to the base IL and shows highly temperature dependency. Experimental enhanced shear viscosity could be predicted at a nanoparticle concentration up to 0.18 vol% and at higher concentration, the conventional viscosity model underpredicted the experimental measurements.

-The thermal conductivity of the NEILs is enhanced by ~11% for a nanoparticles loading of 0.9 vol% and the measured thermal conductivity of NEILs shows higher values than those predicted by Maxwell's model within the investigated temperature range. Heat capacity of NEILs enhanced by ~49% for a nanoparticles loading of 0.9 vol%.

-The convective heat transfer coefficient is higher for the NEILs compared to the base IL. The enhancement of heat transfer coefficient is much higher than the thermal conductivity enhancement depending on the nanoparticle concentration. In a particular concentration and Reynolds number, enhancement of convective heat transfer is more in the entrance region. Also, the turbulent flow regime shows higher enhancement compared to the laminar flow. The enhancement in heat transfer coefficient may be due to the enhanced thermal conductivity and particle migration behavior in the boundary layer.

-The experimental results of this study will assist to understand the flow behavior and thermal performance of NEILs. The enhanced thermal performance of NEILs will help to develop energy efficient HTF for the next generation CSP system. However, the more specific mechanism of the heat transfer enhancement of the NEILs and nanoparticles' size and shape effect needs to be explored. The future research would study the effect of particle morphology on thermal performance of NEILs and find a specific particle size and shape for maximum enhancement.

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Figure 1:

Cation

Anion

Figure 2:

(a)

(b)

Figure 3:

Figure 4:

Figure 5:

(a)

(b)

(c)

(d)

(e)

Figure 6:

(a)

(b)

(c)

Figure 7:

Figure 8:

Figure 9:

Figure 10:

(a)

(b)

Figure 11:

(a)

(b)