A numerical approach in the assessment of a new class of fluids performance in laminar flow

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Abstract. The present paper focuses on the analysis of the thermal conductivity for both base fluid and their ionanofluids. Sequently, an analysis of the new heat transfer fluids behavior in laminar flow was performed to compare the experimental and theoretical results. In terms of experimental, the results showed a higher thermal conductivity for the ionanofluids with the highest nanoparticles concentration. Plus, the thermal conductivity is decreasing slightly with nanoparticles mass fraction while it is almost constant with increasing temperature. On the other hand, in the case of thermal conductivity theoretically determined, this is decreasing with increasing temperature. Furthermore, Mouromtseff number was used to evaluate the relative heat transfer capacity of different fluids. Higher Mouromtseff indicates a better heat transfer capacity of a certain fluid compared to a regular one. Concluding, the present study compared the thermal conductivity for base fluid and Al₂O₃ dispersed in [C₂mim][CH₃SO₃]:H₂O in the particle concentration range of 1–10 % wt and temperatures between 283.50 and 333.38 K. The results demonstrate that the thermal conductivity enhances with concentration increase. The maximum thermal conductivity enhancement of 10.2% was found for 10 % wt of ([C₂mim][CH₃SO₃]:H₂O) + Al₂O₃ ionanofluids. An increased Mouromseff number was noticed for theoretical thermal conductivity.

1. Introduction

Ionic liquids are a liquid salt that can be successfully used in solar energy applications. They become liquids under a certain temperature (for example 100°C) and have unique properties such as negligible vapor pressure, non-inflammability, high thermal conductivity, high density, thermal stability, making them so distinct compared to conventional liquids [1]. The use of ionic liquids opens up new possibilities for obtaining new types of fluids prepared using an environmentally friendly, recyclable process and applicability in industry. Since the publication of the first article in 2010 about ionanofluids [2], special attention has been paid to this new type of heat transfer fluid by different research groups [3-5]. This can be explained not only by the properties and interesting behavior of these nanosystems, but also by the large number of potential industrial applications triggered by nanofluid research, and as a result of the extraordinary opportunities offered by the use of ionic liquids. On the other hand, thermal transfer simulation is an advanced technique that primarily leads to the decrease of experimental effort. Different researchers [6, 7] studied the performance and
characteristics of the heat transfer flux for different nanofluids with different nanoparticles and base fluids. The experimental results of heat transfer by natural convection for ionic liquid [C$_{2}$mim] [NTf$_{2}$] in the rectangular cavity with different aspect ratios was published by Paul et al. [8]. Liu et al. [9] have studied experimentally the effects of thermal conductivity of nanofluids, based on ethylene glycol and synthetic motor oil and nanoparticles of multi-wall carbon nanotubes. Actual amount of experimental data regarding the ionanofluid properties, in particular thermal conductivity, remains quite limited, and to estimate the thermal conductivity, researchers often turned to available theoretical formulas. In the present work, besides the experimental results, three common models were selected and an investigation of the effect of these models used to predict ionanofluid thermal conductivity for laminar flow is accomplished.

2. Experimental

2.1. Materials
The ionic liquid 1-ethyl-3-methylimidazolium methanesulphonate [C$_{2}$mim][CH$_{3}$SO$_{3}$] (CAS 145022-45-3) with purity ≥ 95% and with ≤ 0.5% water content was purchased from SIGMA-ALDRICH. The ionic liquid has a molecular weight of 206.26 g/mol. The water used in the study was produced using a Milli-Q 185 Plus system (Millipore Ltd., Watford, UK) with a resistivity of 18.2MWcm at 298K. The Al$_{2}$O$_{3}$ aluminum oxide nanoparticles were purchased from Sigma Aldrich, CAS 1344-28-1 with a nanoparticle size of 50μm, the surface area being ≥40m$^{2}$/g (BET) and a molecular weight of 101.96 g/mol.

2.2. Thermal conductivity measurement
Thermal conductivity of the ionanofluids was determined using a KD2 Pro Thermal Properties Analyzer (Decagon Devises, Inc. Pullman, USA) coupled with a 1.3mm diameter KS-1 probe and a length of 60mm designed to fit with time and temperature data. The estimated standard uncertainty is better than the range of 0.01W m$^{-1}$ K$^{-1}$. Approximately 10ml of ionanofluid was used for each test, then the flask filled with ionanofluid was placed in a constant and fixed temperature bath. The needle of the KS-1 probe is placed in the middle of the vial and held for 15 minutes to achieve a temperature equilibrium.

After determining the precision of the sensor, the thermal conductivity was measured at least five times at constant temperatures between 10 and 60°C and the mean values of the measurements were reported. These values are shown in table 1. Table 2 also shows the thermal conductivity values for pure ionic liquid, water and ionic liquid plus water.

| Temperature [K] | ([C$_{2}$mim][CH$_{3}$SO$_{3}$]:H$_{2}$O)0.25 + Al$_{2}$O$_{3}$ -0.010 [W/m K] | ([C$_{2}$mim][CH$_{3}$SO$_{3}$]:H$_{2}$O)0.25 + Al$_{2}$O$_{3}$ -0.050 [W/m K] | ([C$_{2}$mim][CH$_{3}$SO$_{3}$]:H$_{2}$O)0.25 + Al$_{2}$O$_{3}$ -0.100 [W/m K] |
|----------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| 283.48         | 0.194                                                         | 0.201                                                         | 0.210                                                         |
| 293.40         | 0.195                                                         | 0.201                                                         | 0.210                                                         |
| 303.37         | 0.193                                                         | 0.199                                                         | 0.208                                                         |
| 313.37         | 0.193                                                         | 0.199                                                         | 0.207                                                         |
| 323.36         | 0.193                                                         | 0.198                                                         | 0.208                                                         |
| 333.37         | 0.192                                                         | 0.198                                                         | 0.207                                                         |
The highest thermal conductivity is noticed for the ionanofluids with the highest concentration of nanoparticles. Plus, the thermal conductivity is decreasing slightly with mass fraction while it is almost constant with increasing temperature.

**Table 2.** Experimental thermal conductivity of [C$_2$mim][CH$_3$SO$_3$], [C$_2$mim][CH$_3$SO$_3$]:H$_2$O)0.25 and H$_2$O depending of temperature.

| Temperature [K] | [C$_2$mim][CH$_3$SO$_3$] [W/m K] | ([C$_2$mim][CH$_3$SO$_3$]:H$_2$O):0.25 [W/m K] | H$_2$O [W/m K] |
|----------------|----------------------------------|---------------------------------|----------------|
| 283.50         | 0.190                            | 0.202                           | 0.580          |
| 293.42         | 0.188                            | 0.201                           | 0.598          |
| 303.38         | 0.187                            | 0.202                           | 0.615          |
| 313.38         | 0.187                            | 0.201                           | 0.630          |
| 323.38         | 0.186                            | 0.201                           | 0.643          |
| 333.38         | 0.186                            | 0.201                           | 0.654          |

H$_2$O has higher thermal conductivity compared to [C$_2$mim][CH$_3$SO$_3$], and the thermal conductivity increases with the temperature. Thermal conductivity remains near constant for [C$_2$mim][CH$_3$SO$_3$] and ([C$_2$mim][CH$_3$SO$_3$]:H$_2$O) at different concentrations, H$_2$O having the highest thermal conductivity compared to these fluids.

### 2.3. Theoretical models

The thermophysical properties of the solid oxide nanoparticles adopted to be used in this study are indicated in table 3 [10].

**Table 3.** Thermophysical properties of nanoparticles at 293 K. [10]

| Property                     | Nanoparticle (Al$_2$O$_3$) |
|------------------------------|----------------------------|
| Specific heat [J/kg K]       | 765                        |
| Density [kg/m$^3$]           | 3970                       |
| Thermal conductivity [W/m K] | 40                         |

The data obtained were compared with the predictions of the theoretical thermal conductivity model of the solid-liquid mixture.

#### 2.3.1. Heat transfer estimation by figure of merit

The Mouromtseff number is a figure of merit (FOM) to compare the relative heat transfer capacity of different fluids. This number is proportional to the convective heat transfer coefficient and only considers the contribution of the thermophysical properties of the fluid for a geometry and a fixed speed. Higher Mo indicates a better heat transfer capacity of fluids. The Mouromtseff number for the fully developed internal flow is given by equation (1), [11]:

$$Mo = \frac{\rho^a K^b \varepsilon^c \mu^d}{\mu^e}$$

where exponents a, b, d and e take values corresponding to the mode of heat transfer of interest and corresponding correlation of heat transfer. For fully developed laminar flow using equation (2):
\[
FOM = \frac{Mo_{inf}}{Mo_{bf}} = \frac{h_{inf}}{h_{bf}} = \frac{K_{inf}}{K_{bf}}
\]  

(2)

2.3.2. Thermal conductivity theoretical model

Thermal conductivity can be estimated with the Maxwell model by equation (3), [12]:

\[
\frac{K_{eff}}{K_{bf}} = \frac{K_p + 2K_{bf} + 2\varphi_p(K_p - K_{bf})}{K_p + 2K_{bf} - \varphi_p(K_p - K_{bf})}
\]

(3)

where \(k_p\) is the thermal conductivity of the dispersed particles, \(k_{bf}\) is the thermal conductivity of the dispersion liquid, and \(\varphi\) is the particle volume concentration of the suspension. This model can estimate well the thermal conductivity for nanoparticles suspension in water, especially in regard to alumina, so we decided to select it for this comparison.

For the estimation of thermal conductivity of liquid mixture some analytical methods [13] have been proposed. Li [13-17] proposed the following equation (see equations (4, 5, 6)) for estimating the thermal conductivity of liquid mixture \(\lambda_m\):

\[
\lambda_m = \sum_{i=1}^{n} \sum_{j=1}^{n} \Phi_i \Phi_j \lambda_{ij}
\]

(4)

where

\[
\lambda_{ij} = 2(\lambda_i^{-1} + \lambda_j^{-1})^{-1}
\]

(5)

and

\[
\Phi_i = \frac{x_i V_i}{\sum_{j=1}^{n} x_j V_j}
\]

(6)

\(\Phi_i\) is the superficial volume fraction of \(i\) and \(V_i\) the molar volume of pure component. For a binary system, Li equation reduces to equation (7):

\[
\lambda_m = \Phi_1^2 \lambda_1 + 2\Phi_1 \Phi_2 \lambda_{12} + \Phi_2^2 \lambda_2
\]

(7)

In above equation \(\Phi_1\) and \(\Phi_2\) are termed as volume fractions of component 1 and 2.

3. Results and discussion

Mo number in laminar flow is estimated by the ratio of the thermal conductivities of the two fluids: base fluid and the ionanofluid. In this research a comparison was performed in terms of Mo number for two situations:
- estimation of Mo when thermal conductivity is experimentally measured
- estimation of Mo when thermal conductivity is analytically determined using the law of mixtures and Maxwell model. In table 4 are the results of Mouromtseff number.
Table 4. Results of Mouromtseff number (FOM) with experimental estimation of thermal conductivity.

| IONANOFLOUID | BASE FLUID | TAPE | EXPERIMENTAL ESTIMATION |
|--------------|------------|------|-------------------------|
| ([C\text{2}mim][CH\text{3}SO\text{3}]:H\text{2}O) 0.25 + Al\text{2}O\text{3} - 1% | [W/m K] | 0.9604 | 0.9950 |
| | | 0.9701 | 1.0000 |
| | | 0.9554 | 0.9851 |
| | | 0.9602 | 0.9900 |
| | | 0.9602 | 0.9851 |
| | | 0.9552 | 0.9851 |
| [C\text{2}mim][CH\text{3}SO\text{3}]:H\text{2}O) 0.25 + Al\text{2}O\text{3} - 5% | [W/m K] | 1.0396 | 1.0448 |
| | | 1.0297 | 1.0299 |
| | | 1.0348 | 1.0299 |
| [C\text{2}mim][CH\text{3}SO\text{3}]:H\text{2}O) 0.25 + Al\text{2}O\text{3} - 10% | [W/m K] | 1.0448 | 1.0299 |
| | | 1.0299 | 1.0299 |

Mo number using theoretical estimation of thermal conductivity was accomplished following several steps, as are depicted further. Firstly, the volume concentrations of ionanofluids were calculated based on weight concentration of the dispersions using equation (8):

\[
\frac{1}{x_{\text{vol}}} = 1 + \frac{\rho_p}{\rho_f} \left( \frac{1-x_{\text{wt}}}{x_{\text{wt}}} \right)
\]

where \(x_{\text{vol}}\) and \(x_{\text{wt}}\) are the volume and mass fraction, accordingly while \(\rho_p\) and \(\rho_f\) are the nanoparticles and base fluid density. The nanoparticles density at 25\(^\circ\)C were adopted from Dawood et al. [18] as: \(\rho_{\text{alumina}} = 3970.00\ \text{kg/m}^3\), \(\rho_{\text{water}} = 997.05\ \text{kg/m}^3\) and the base fluid (([C\text{2}mim][CH\text{3}SO\text{3}]:H\text{2}O):0.25) experimental density at 25\(^\circ\)C is \(\rho = 1234.40\ \text{kg/m}^3\). In table 5 one can notice also the correspondence between mass concentration (\% wt) and volume concentration (\% vol).

Table 5. Prepared ionanofluids.

| IONANOFLOUID TYPE | BASE FLUID | MASS CONCENTRATION OF NANOPARTICLES, \(\gamma, \%\text{wt}\) | VOLUME CONCENTRATION OF NANOPARTICLES, \(\phi, \%\text{vol}\) |
|-------------------|------------|---------------------------------|---------------------------------|
| alumina ionanofluids | ionic liquid plus water | 1\% wt Al\text{2}O\text{3} | 0.31\% vol |
| alumina ionanofluids | ionic liquid plus water | 5\% wt Al\text{2}O\text{3} | 1.61\% vol |
| alumina ionanofluids | ionic liquid plus water | 10\% wt Al\text{2}O\text{3} | 3.33\% vol |

The results of calculation of \(\lambda_{\text{m}}\) by equations (4) and (7) along with the experimental values at different temperatures (298.50 K and 333.38 K) are recorded in tables 6 and 7.

Table 6. Properties of ionic liquid and water at 298.15 K.

| NAME | IONIC LIQUID | WATER |
|------|-------------|-------|
| m (molecular mass) | 206.26 g/mol | 18.01 g/mol |
| \(\rho\) (density) | 1239.20 kg/m\(^3\) | 997.05 kg/m\(^3\) |
| x (molar fraction) | 0.75 | 0.25 |
| V (molar volume) | 0.166 | 0.018 |
| \(\Phi\) (volume fraction) | 0.965 | 0.034 |
Table 7. Thermal conductivity of liquid mixture at 283.1 – 333.38 K.

| T/ [K] | \( \lambda_{m} \) theoretical |
|-------|-------------------------------|
| 283.50 | 0.1963                        |
| 293.42 | 0.1945                        |
| 303.38 | 0.1936                        |
| 313.38 | 0.1937                        |
| 323.38 | 0.1928                        |
| 333.38 | 0.1929                        |

The results of calculation of \( \lambda_{m} \) by Eqs (4) and (7) along with the experimental values at different temperatures (283.05 K and 333.38 K) are recorded in table 7 and shows that thermal conductivity is decreasing slightly with increasing temperature. A perusal of tables 2 and 7 shows a decent agreement between the experimental and estimated values of the thermal conductivity. Thermal conductivity variation with temperature for (IL:H₂O)0.25 experimental and theoretical is depicted in figure 1.

Figure 1. Thermal conductivity of ([C₂mim][CH₃SO₃]:H₂O)0.25 experimental and theoretical depending on the temperature.

In terms of experimental determination the results showed an decrease in thermal conductivity, and the effect of temperature is not obvious as there are few changes. On the other hand, in the case of thermal conductivity theoretically determined is decreasing with increasing temperature.

Experimental measurements of the thermal conductivity ([C₂mim][CH₃SO₃]:H₂O)0.25 + Al₂O₃ ionanofluids are compared with values calculated from law of mixtures and Maxwell model. The highest thermal conductivity is noticed for the ionanofluids with the highest concentration of nanoparticles. The results presented in figure 2, showed a decrease in thermal conductivity, and the effect of temperature is obvious, as there are changes. The experimental results show lower values of thermal conductivity compared to the theoretical results.

The highest Mouromseff number values were obtained for ([C₂mim][CH₃SO₃]: H₂O) + Al₂O₃ - 0.100 and indicates a better heat transfer. For all fluids, the Mouromseff number remains constant with temperature rise (see figure 3). In conclusion, the ionanofluid with the better heat transfer capacity is the ionanofluid with the highest nanoparticles concentrations.
Figure 2. Effect of temperature variation on the thermal conductivity of ([C$_2$ mim][CH$_3$SO$_3$]:H$_2$O)$_{0.25}$ + Al$_2$O$_3$ with different mass fraction (0.010, 0.050, 0.100) ionanofluids experimental and theoretical.

Figure 3. Mouromtseff number of ([C$_2$ mim][CH$_3$SO$_3$]:H$_2$O)$_{0.25}$ + Al$_2$O$_3$ with different mass fraction (0.010, 0.050, 0.100) ionanofluids experimental and theoretical.

4. Conclusions
The present study compared the thermal conductivity for base fluid and Al$_2$O$_3$ dispersed in [C$_2$ mim][CH$_3$SO$_3$]:H$_2$O in the particle concentration range of 1–10 % wt and temperatures between 283.50 and 333.38 K. The results demonstrate that, thermal conductivity enhances with concentration.
The maximum thermal conductivity enhancement of 3.9% and 10.2% was found for 10% wt of ([C₃ mim][CH₃SO₃]:H₂O) + Al₂O₃ ioni nanofluids, calculated with Mouromseff number for theoretical and experimental thermal conductivity.

In conclusion, even if the heat transfer performance is augmented by suspension of nanoparticles in base fluid, a substantial intensification in experimental and numerical studies is needed.

5. References
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