Heat transfer performance of $\text{Al}_2\text{O}_3 - ([C4mim][\text{NTf}_2])$ nano-suspension in a $2-D$ channel for application in a flat plate solar collector

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Abstract. IoNanofluids are a recent class of nanotechnology based heat transfer fluids synthesized by suspending nanoparticles in ionic liquids. These IoNanofluids are superior to conventional nanofluids due to their higher thermal stability and are more suitable for high temperature applications. In this study, a numerical analysis of laminar forced convection in a 2-D channel using $\text{Al}_2\text{O}_3$ in $([C4mim][\text{NTf}_2])$ IoNanofluids has been presented. Flow Reynolds number ($Re$) is varied from 250 to 1000, particle volume fraction ranges from 0 % to 2.5 % and three inlet temperatures of 293 K, 313 K and 333 K have been taken into account. A uniform heat flux of 1000 W m$^{-2}$ is applied on the top wall to resemble the scenario in a flat plate solar collector. Governing equations of flow and heat transfer has been solved using a Finite Volume Method based commercial software ANSYS Fluent 15.0. Furthermore, unique feature of this study is that the thermo-physical properties of IoNanofluids are considered to be temperature dependent. Results indicate that IoNanofluids provide better cooling than conventional water based coolants. The top surface of the channel experiences a decrease of upto 4 K at an inlet temperature of 333 K. Mean Nusselt number and heat transfer coefficients increase by the addition of nanoparticles to the ionic basefluid. IoNanofluids show better heat transfer enhancement than conventional water based nanofluids at higher temperatures. Hence, it can be concluded that IoNanofluids have a higher potential to be employed in high temperature applications.

Keywords— Ionic Nanofluids, Thermal Stability, Solar Collector, 2-D channel, Heat Transfer.

1. Introduction

Solar energy harvesting is a well-known technology to harvest solar energy which finds applications in several industrial and residential setups. In recent times, many researchers have been working on improving the performance of solar collectors. Several works are available in recent literature on performance analysis of solar collectors. A numerical study by Rejeb et al. [1] proposed optimal operating conditions in a semi-arid climate, for a solar collector to have maximum efficiency. Ahmed and Mohammed [2] evaluated the performance improvement in solar collector while employing porous media. Yandri [3], numerically analyzed the relevance of Joule-heating in a solar PVT system, to swimming pool heating and low temperature source heat pumps. A detailed review by Agathokleous and Kalogirou presents the state of the art development in this technology [4]. In general, the common working fluids employed in solar
collectors are water, different types of oils, etc. Thus, the performance of these solar energy harvesting devices are limited by low thermal conductivity of these common working fluids.

With recent advancements in the field of nanofluids, which have superior thermal properties as compared to pure fluids [5, 6, 7, 8, 9], several researchers have ventured to study the performance of nanofluids in solar collectors [10]. Rose et al. [11] studied the performance of nanofluids in direct solar radiation collectors. Similar analyses on performance of nanofluids in direct absorption solar collectors were carried out by many researchers all around the world [12, 13]. Some other researchers have worked on the application of nanofluids on concentrated solar collectors [14, 15]. Xu and Kleinstreuer [16] developed a novel concentration photo-voltaic thermal energy co-generation system, where nanofluids were used a working fluids. It was reported that, employment of nanofluids resulted in a significant increase in overall efficiency of the system. Furthermore, many other researchers have reported works on the application of nanofluids in flat plate solar collectors. It was evident that the usage of nanofluids as working fluids in flat plate solar collectors resulted in a notable increase in thermal efficiency of the system [17, 18, 19].

A detailed review of the available literature on the application of nanofluids in solar energy harvesting reveals that nanofluids have resulted in a notable enhancement in energy harvesting performance. But, the application of conventional nanofluids were limited due to poor thermal stability. At higher temperatures the base fluids (water, oil, ethylene glycol) would vaporise, leaving behind the nanoparticles. At the wake of problems regarding limitations in use of traditional base fluids at high temperatures, a new class of nanofluids called IoNanofluids were discovered [20]. They were similar to the conventional nanofluids, but had Ionic fluids as their base fluids. These ionic fluids are molten salts or salts, that stay in liquid phase from room temperature (293 K) to extremely high temperatures (> 1000 K) [21]. Being relatively new in its conception, the field of IoNanofluids is growing with alacrity, and has seen the emergence of several literature on its thermo-physical properties [20, 21, 22, 23]. Based on these studies, as a testament to their superior properties over the conventional nanofluids, they possess higher thermal stability and better thermo-physical properties.

![Graphical view of the computation domain.](image)

Figure 1: Graphical view of the computation domain.

With respect to IoNanofluids, there are works reported in literature, that deal with experimental measurement of thermo-physical properties of IoNanofluids. Only a very few studies are recently reported in numerical analysis of flow and heat transfer performance of IoNanofluids [24, 20, 25, 26]. More specifically, only three studies are available on application
of IoNanofluids in solar energy harvesting systems [25, 27, 28]. Much more detailed analysis on application of IoNanofluids in solar energy harvesting systems is essential in this topic of research. In an attempt to bridge this gap, this study presents a numerical analysis of steady, laminar forced convective flow of $\text{Al}_2\text{O}_3$ in ([C4mim][NTf2]) IoNanofluid in a 2-D heated channel. The geometry chosen is a tube with rectangular cross-section, which is commonly used in flat plate solar collectors. Apart from the role of Reynolds number and particle volume fraction, temperature dependence of the thermo-physical properties of IoNanofluids is also taken into account. Furthermore, a comparison of performance of IoNanofluids with conventional water based nanofluids has also been presented.

Table 1: Temperature dependent thermo-physical properties of $\text{Al}_2\text{O}_3$ – ([C4mim][NTf2]) IoNanofluid adopted from experimental data available in literature [20].

| S. No | Temperature | $\phi = 0\%$ | $\phi = 0.5\%$ | $\phi = 1\%$ | $\phi = 2.5\%$ |
|-------|-------------|-------------|-------------|-------------|-------------|
|       | Specific Heat Capacitance, $c_p$ (J/kgK) |           |           |           |           |
| 1     | 293 K       | 1749        | 1900        | 2100        | 2400        |
| 2     | 313 K       | 1749        | 1950        | 2235        | 2465        |
| 3     | 323 K       | 1743        | 2038        | 2256        | 2530        |
| 4     | 333 K       | 1744        | 2040        | 2270        | 2600        |
|       | Viscosity, $\mu$ (kg/ms) |           |           |           |           |
| 1     | 293 K       | 0.06283     | 0.064      | 0.075      | 0.0125      |
| 2     | 313 K       | 0.0287      | 0.032      | 0.035      | 0.070       |
| 3     | 323 K       | 0.0215      | 0.022      | 0.029      | 0.052       |
| 4     | 333 K       | 0.0162      | 0.017      | 0.020      | 0.039       |
|       | Thermal Conductivity, $k$ (W/mK) | | | | |
| 1     | 293 K       | 0.0126      | 0.129      | 0.134      | 0.138      |
| 2     | 313 K       | 0.125       | 0.127      | 0.133      | 0.136      |
| 3     | 323 K       | 0.124       | 0.128      | 0.132      | 0.135      |
| 4     | 333 K       | 0.123       | 0.127      | 0.132      | 0.134      |
|       | Density, $\rho$ (kg/m$^3$) | | | | |
| 1     | 293 K       | 1411.98     | 1450       | 1460       | 1506       |
| 2     | 313 K       | 1391.64     | 1428       | 1442       | 1483       |
| 3     | 323 K       | 1387.06     | 1410       | 1431       | 1470       |
| 4     | 333 K       | 1386.06     | 1390       | 1425       | 1453       |

2. Mathematical formulation and problem statement
A laminar, steady, forced convective flow of $\text{Al}_2\text{O}_3$ in ([C4mim][NTf2]) IoNanofluid in a tube of rectangular cross section with dimensions $0.01 \times 0.16 \times 2$ m has been numerically studied. A schematic sketch of the flow configuration considered for the analysis is presented in Fig. 1. The flow is considered to be laminar in the Reynolds number range of 250 to 1000, where the particle concentration ($\phi$) and inlet temperature ($T_\infty$) are varied as $0 \% \leq \phi \leq 2.5 \%$ and $293 \, K \leq T_\infty \leq 333 \, K$, respectively. A uniform heat flux ($\dot{q}$) of 1000 Wm$^{-2}$ is applied on the
upper surface to simulate the solar radiation, the bottom surface is considered to be adiabatic. The IoNanofluid enters the channel at the inlet, with an uniform velocity \( u_\infty \) in \( x \)-direction and free stream temperature \( T_\infty \). The governing equations of flow and heat transfer are presented as follows:

**Continuity equation**

\[
\nabla \cdot (\rho \mathbf{V}) = 0
\]

**Momentum equation**

\[
\nabla \cdot (\rho \mathbf{V} \cdot \mathbf{V}) = -\nabla P + \mu \nabla^2 \mathbf{V}
\]

**Energy equation**

\[
\nabla \cdot (\rho \mathbf{V} C T) = \nabla \cdot (k \nabla T)
\]

In the above Eqs. (1) to (3), \( \rho \), \( \mathbf{V} \), \( P \), \( C \) and \( T \) represent density, velocity vector, pressure, specific heat and temperature, respectively.

2.1. *Thermo-physical properties*

Present study considers \( \text{Al}_2\text{O}_3 - ([\text{C}4\text{mim}][\text{NTf}_2]) \) IoNanofluid to be a homogeneous fluid with effective thermo-physical properties as presented in Table 1 which are adopted from experimental data available in literature [20, 24].

Figure 2: Comparison of results from the present code with Shah’s correlation [29] at (a) \( T_\infty = 293 \text{ K} \), (b) \( T_\infty = 313 \text{ K} \) and (c) \( T_\infty = 333 \text{ K} \)
3. Numerical methodology and grid generation
The modeling of geometry and meshing was carried out using ANSYS ICEM CFD 15.0. The

governing equations were solved along with suitable boundary conditions using the commercial
FVM solver ANSYS FLUENT 15.0. A SIMPLE algorithm based pressure-velocity coupling has
been employed. The convective terms are discretized using third-order accurate QUICK scheme.
The discretized equations are sequentially solved using an iterative approach with a convergence
criteria for residuals equal to $10^{-7}$. A non-uniform grid with more fine grid near the walls has
been used to capture the sharp gradients in flow and temperature field. A detailed grid analysis
has been carried out to ensure consistency of the results. Three grids, namely, $18 \times 300$, $35 \times 600$
and $70 \times 1200$ have been taken into account for the grid sensitivity analysis. As presented in [30],
$35 \times 600$ has been taken into account, considering the accuracy and computational requirements.

4. Code validation
In order to ensure the reliability of the results presented in the present study, results from the
present code were compared with Shah’s correlation as suggested by Utomo et al. [31], while
using water as working fluid. For validation, a uniform heat flux of $5000 \text{ Wm}^{-2}$ was imposed
on both the top and bottom surfaces. The comparison of results from present code and the
Shah’s correlation are presented in Fig. 2. It is clearly observed that the results from present
code match closely with the Shah’s correlation.

5. Results and Discussion
In this study, laminar forced convection of $\text{Al}_2\text{O}_3$ in $([\text{C}4\text{mim}][\text{NTf}_2])$ IoNanofluid in a $2-D$
heated channel is numerically studied. The configuration taken in to account is rectangular
tube, as used in flat plate PV/T collectors. Three different inlet temperatures, namely $293 \text{ K}$,
$313 \text{ K}$ and $333 \text{ K}$ have been taken into account. The particle volume fraction and flow Reynolds
number are varied as $0 \%$ to $2.5 \%$ and $250 \leq \text{Re} \leq 1000$, respectively.

Figure 3 presents the temperature distribution along the top wall ($T_{\text{Wall}}$) at $\text{Re} = 1000$ and
$0 \% \leq \phi \leq 2.5 \%$, (a) $T_\infty = 293 \text{ K}$, (b) $T_\infty = 313 \text{ K}$ and (c) $T_\infty = 333 \text{ K}$. It is noted that the
temperature at $x = 0 \text{ m}$ is same as the inlet temperature and shows an immediate increase in the
developing region upto $x = 0.5 \text{ m}$. Then, due to the constant heat flux applied to the wall surface,
it shows a gradual linear increase in the developed region and finally reaches the maximum value
at the outlet ($x = 2 \text{ m}$). At all inlet temperatures, addition of nanoparticles to the basefluid
resulted in lower temperature profiles. This shows that the addition of nanoparticles leads to
more heat transfer from the wall to fluid. This can be attributed to the increase in thermal
conductivity of the basefluid due to addition of nanoparticles. Peak temperature reached by the
top wall drops by $1.6 \text{ K}$, $2.6 \text{ K}$ and $3.2 \text{ K}$ by addition of $2.5 \%$ volume fraction of nanoparticles,
at inlet temperatures equal to $293 \text{ K}$, $313 \text{ K}$ and $333 \text{ K}$, respectively. This provides a better
operating conditions for the PV cells places on upper surface of the channel [14]. Furthermore,
it can be inferred that the drops in peak temperature are higher at higher inlet temperatures.
This indicates the better performance of IoNanofluids at higher temperatures, which makes them
more promising working fluids for high temperature applications.

Fig. 4 presents the variation of mean Nusselt number at $0 \% \leq \phi \leq 2.5 \%$, $250 \leq \text{Re} \leq 1000$
and $T = 293 \text{ K} & 333 \text{ K}$. The mean Nusselt number is calculated as follows:

$$N_U = \frac{\dot{h}D_h}{k_{nf}}$$  \hspace{1cm} (4)

where, $\dot{h} = \dot{q}/(T_{\text{Wall}} - T_{\text{mean}})$ is the heat transfer coefficient, $D_h$ is the hydraulic diameter,
and $k_{nf}$ is the effective thermal conductivity of IoNanofluids.

As expected, the mean Nusselt number values also increase with increase in flow Reynolds
number at all volume fractions. This indicates that the heat is better convected from the wall.
Figure 3: Temperature profiles along the heated (top) wall of the channel at $Re = 1000$, $0 \% \leq \phi \leq 2.5 \%$, (a) $T_\infty = 293 K$, (b) $T_\infty = 313 K$ and (c) $T_\infty = 333 K$.

at higher flow velocities. The mean Nusselt number is also found to be a function of particle volume fraction. This can be attributed to the increase in thermal conductivity of IoNanofluids with increase in particle volume fraction. For instance, at $Re = 1000$ and $\phi = 2.5 \%$, IoNanofluid shows 25 % and 30 % increase in mean Nusselt number compared to pure ionic basefluid, at $T_\infty = 293 K$, and 333 $K$, respectively. Though the mean Nusselt number values, show similar trend with respect to $Re$ and $\phi$ at both the inlet temperatures, it is to be noted that the increase in mean Nusselt number is high at higher inlet temperatures. This is a clear indication of the superior performance of IoNanofluids at elevated temperatures.

Fig. 5 compares the heat transfer enhancements obtained using water based nanofluids and IoNanofluids in terms of heat transfer enhancement ratio ($E$), which is calculated as follows:

$$ E = \frac{h_{nf}}{h_{bf}} $$

Where, $h_{nf}$ is the average heat transfer coefficient obtained using IoNanofluids/nanofluids and $h_{bf}$ is the average heat transfer coefficient using pure basefluids. The values of ($E$) are always greater than 1. This shows that the addition of nanoparticles ensured heat transfer enhancement in all cases. It is to be noted that the values of $E$ and the increase in $E$ with respect to particle volume fraction are higher for IoNanofluids than the water based nanofluids. This shows the better performance of IoNanofluids at any given volume fraction. Also, it is to be noted that the highest values of $E$ reached by IoNanofluids are around 1.46 and 1.6 at $293 K$ and $333 K$, respectively. This observation, indicates that IoNanofluids lead to higher enhancements in heat transfer at higher temperatures.
6. Conclusions
This study presented a numerical analysis of $Al_2O_3$ in ($[C4mim][NTf2]$) forced convective flow through a $2-D$ channel, similar to the application in a PV/T solar collector. Detailed analysis of the temperature profiles on the heated wall of the channel, demonstrates that utilization of IoNanofluids guarantee better cooling, when compared to pure base fluids. This provides more suitable operating conditions for the PV cell to have higher PV conversion efficiency. Furthermore, the performance of IoNanofluids was compared with that of conventional water based nanofluids. It was observed that IoNanofluids exhibited better performance than the conventional water based nanofluids. Moreover, the performance of IoNanofluids was notably higher than water based nanofluids, at elevated temperatures. A more detailed study can be carried out in future to analyze the pressure drop while using IoNanofluids, which will give better insights on application of IoNanofluids to real time engineering applications. On the basis of observations in the present study, it can be concluded that IoNanofluids led to notable heat transfer enhancements in the considered flow configuration. Adding to that, IoNanofluids outperformed conventional water based nanofluids, especially at higher operating temperatures. Hence, it can be concluded that IoNanofluids have a higher potential to be employed in medium to high temperature applications.
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