Convective heat transfer enhancement with graphene nanoplatelet/platinum hybrid nanofluid

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ABSTRACT

The work here looked into heat transfer performance in addition to friction loss of graphene nanoplatelet (GNP). Platinum (Pt) hybrid nanofluids. The experiments were performed with non-changing limit parameters of heat-flux. Nanofluid movement was turbulent at a weight percentage ranging between 0.02 and 0.1%, with the Reynolds number from 5000 to 17,500. The experimental findings revealed that compared with the base liquid, all nanofluid samples had higher heat transfer abilities. Nusselt number elevation and the increment of the heat transfer coefficient were found to be dependent on Reynolds number, and the weight concentration of the nanocomposite. The greatest value recorded for Nusselt number was 28.48%, accompanied by a 1.109-fold penalty. There was a rise in friction factor with regards to the highest load of nanocomposite (0.1 wt%), with the Reynolds number of 17,500.

1. Introduction

Recently, hybrid nanofluids have caught the attention of many researchers. Hybrid suspensions are an advanced class of nanofluids prepared by dispersing a nanocomposite in a base liquid. A hybrid nanocomposite may be viewed as a combined material that has consequent to a synthesis process acquired physical and other distinct properties of two or more single materials, allowing these properties to be in an analogous phase. The key purpose of producing such nanofluids has to do with achieving a combination of characteristics belonging to single-phase substances that fail to have a range of desirable properties needed to serve a specific aim. In many industrial applications, a trade-off between some characteristics is required. A single material may have good rheological or thermal properties, but that may not be enough for industrial applications. This is what inspires researchers to develop hybrid nanofluids. Hybrid nanofluids are expected to have higher thermal conductivity than single-phase nanofluids because of the synergistic phenomena [1–5].

The advanced characteristics of nanocomposites have attracted researchers who then embarked on an effort to produce hybrid nanofuids [6–12]. Early attempts to prepare hybrid nanofluids were made by using metal and/or metal oxide nanocomposites. For example, to develop their hybrid nanofluids, Suresh et al. [13,14] used a thermo-chemical synthesis method that employed an ultrasonic vibrator. They observed a remarkable improvement in thermal conductivity after they hybridized Al2O3 and Cu nanoparticles. Nine et al. [15] prepared hybrid Cu/Cu2O using a wet ball milling process in water. They used a two-step mechanical method for making a stable hybrid nanofluid, with the size of the final particles being about 20 μm. However, they reported nonsignificant thermal conductivity enhancement of the hybrid nanofluid as compared with the single-phase nanofluid (Cu/water). An Ag/TiO2 nanocomposite dispersed in water was studied by Batmunkh et al. [16]. Having investigated the ability of the nanofluid to conduct heat by using the transient hot-wire technique, the researchers concluded that adding the nanocomposite to the base liquid could enhance the thermal conductivity of TiO2 water based nanofluid.

Carbon based nanomaterials have a bunch of unique characteristics, like considerable heat and current transduction potentials, physical...
strength and chemical stability [17–19]. These properties have attracted the attention of researchers. Many investigators have thus been conducted to manipulate and measure the thermo-physical properties of carbon-based hybrid nano-fluids [20]. For example, Sundar et al. [4] proposed an MWCNT-Fe$_3$O$_4$ nanocomposite to produce a hybrid nano-fluid. Experimental data suggested a 29% rise in thermal conductivity a 0.3% volume concentration ratio in water. On the other hand, Baby and Sundara [21] reported a hybrid CuO-HEG nano-fluid, functionalized hybrid graphene and no added surface active agents. The product they introduced proved to be able to convey heat with a 28% better efficiency. Using a volume ratio of 0.04%, a later report on Ag/MWCNT-HEG hybrid nano-fluids by the same researchers [22] demonstrated an 8% increase in thermal conductivity for a volume fraction of 0.04% at 25°C for Ag/MWCNT-HEG hybrid nano-fluids. We had shown earlier that GNP-Ag aqueous nano-fluids could be produced with a simple functionalization method. Our work revealed then a 22.22% increase at a ratio of 0.1% weight concentration of nanocomposite.

Investigating heat transfer and pressure drop is a key area in the field of carbon-based hybrid nano-fluids. Having looked into the heat transfer coefficient of CuO-HEG in water and ethylene glycol, Baby and Sundara [21] found marked elevation of the heat transfer performance, with greater increases in heat transfer coefficient in EG-based hybrid nano-fluids. Chen et al. [23] reported remarkable improvement in heat transfer ability of CNT-Graphene water-based nano-fluid for a Laminar forced convective fluid flow. Our research group [6] also investigated a GNP-Ag aqueous nano-fluid in terms of its Nusselt number and friction factor values. As compared with distilled water, the nano-fluid showed an impressive increase in the Nusselt value, amounting to 32.7% at 0.1% weight concentration, whereby Reynolds was at a value of 17,500; and friction grew 1.08 folds. The literature on thermal conduction improvement in hybrid nano-fluids is extensive, with all reports confirming that carbon-based nanocomposites are very promising candidates for suspension in base fluids [4,24,25].

This study is a pioneer effort in which the researchers investigate a graphene nanoplatelet/platinum (GNP-Pt) aqueous hybrid nano-fluid with regards to its heat transfer coefficient and friction factor values at a turbulent condition. The study utilised a special square-shaped heated pipe at a steady heat-flux status. These researchers had previously reported on the synthesis, preparation and thermos-physical properties of the aforementioned hybrid nano-fluid [26]. However, prior to this work, no studies had looked thoroughly into the convective heat transfer coefficient of a GNP-Pt hybrid nano-fluid at a turbulent flow condition.

2. Experimental set up and procedure

2.1. Experimental test rig

Quantifications related to the convective heat transfer coefficient were performed using a well-designed system. Fig. 1 depicts the arrangement of the testing system. The system mainly comprised of a flow loop, a heater, a chiller and a data acquisition apparatus. The flow loop was made up of multiple components, including a pump and a storage tank. The test section featured a 1.4 m long stainless-steel square pipe, which it would pour back into the storage tank. Upkeep of the hydrodynamic entrance length ($l = 140 \, d$) is always needed to achieve fully developed flow. To quantify the flow rate of the nano-fluid, we placed a flow meter near the pump’s outlet. The chiller played a major role in keeping the outlet and the inlet temperatures similar to ensure that the nano-fluids were stable. Decreases in pressure values were reported along the test section to compute the friction factor of nano-fluid. This was achieved by drawing the tapping spots of the Differential Pressure Transmitter (DPT) through both of the pipe’s ends. The nano-fluid thermo-physical characteristics were determined at the mean bulk temperature; and Newton law served to determine the heat transfer coefficient.

2.2. Data processing

Initial tests were performed using the base fluid for calibration purposes before further experimentation to investigate GNP-Pt aqueous nano-fluids. Temperature readings for every nano-fluid were taken under a stable status at the inlet, outlet and walls. Furthermore, the mass flow rate was regularly recorded. A three-hour period was found to be necessary to achieve a stable status for experimentation every time. Eqs. (1) and (2) accordingly show the calculations used to assess the heat released into the test section, and the fraction absorbed by the nano-fluid as it passed through [27]:

\[ P = V \times T \]  
\[ Q = \dot{m} \times C_f \times (T_i - T_f) \]  

\[ \dot{Q} = \frac{Q}{A(T_w - T_0)} \]  

where

\[ T_w = \frac{1}{5} \sum \left( T_{w,i} \right) \]  

\[ T_0 = \frac{\overline{R} + \overline{E}}{2} \]  

\[ A = \pi DL \]

The Nusselt number was calculated as shown in Eq. (4) [28].
\[
Nu = \frac{h \times D_b}{k}
\]  
(4)

where
\[D_b = \frac{4k}{\mu}, \quad A_c: \text{Cross sectional area and } P: \text{Perimeter of the four-sided pipe.}\]

Possible \(Nu\) correlations for turbulent liquid flow are summarized in Eqs. (5)-(7).

To calculate Nusselt values for turbulent flow, Dittus-Boelter [29] proposed Eq. (5), which is relevant in cases whereby \(Re\) is \(> 10^4\) and \(Pr\) is from 0.6 to 200.

\[
Nu = 0.023 Re^{0.8} Pr^{0.4}
\]
(5)

On the other hand, Petukhov [30] believed that Eq. (6) gave a better estimate of the Nusselt value of turbulent flow when \(Pr\) was in a range of \(5 \times 10^{-1} - 2 \times 10^{3}\) and \(Re\) between \(3 \times 10^{5}\) and \(5000 \times 10^3\):

\[
Nu = \frac{\left(\frac{1}{4}\right) Re Pr}{1.07 + 12.7 (\frac{1}{4})^{0.835} (Pr^{0.3} - 1)}
\]
(6)

If \(Re\) is \(> 2.3 \times 10^3\) up to \(1000 \times 10^3\), and \(Pr\) is in the range of \(5 \times 10^{-1} - 2 \times 10^{3}\), Gnielinski [31] would argue that Eq. (7) should be best to compute the Nusselt number for turbulent flow:

\[
Nu = \frac{\left(\frac{1}{4}\right) (Re-1000) Pr}{1 + 12.7 (\frac{1}{4})^{0.3} (Pr^{0.13} - 1)}
\]
(7)

where \(f = (0.79 \ln (Re - 1.64))^{-2}\)

A nanofluid’s friction factor was calculated as follows based on the collected data pertaining to the pressure values along the test section:

\[
f = \frac{\Delta P}{\left(\frac{1}{2}\right) \left(\frac{\rho V}{\mu}\right)^{0.5}}
\]
(8)

Eqs. (9) and (10) demonstrate how to compute \(f\) for completely developed flow:

As to water flow, provided that \(Re\) is in the range of \(3 \times 10^5 - 100 \times 10^5\), one may use Blasius’s equation [32], Eq. (9) to assess \(f\) as follows:

\[
f = 0.3164 Re^{-0.25}
\]
(9)

Otherwise, the friction factor for water flow may be calculated as shown by Petukhov [30] in Eq. (10):

\[
f = (0.790 \ln(Re) - 1.64)^{-2}
\]
(10)

This equation covers a wider range as it is applicable for \(Re\) between \(2.3 \times 10^3\) and \(5000 \times 10^3\).

According to a number of reports [33,34], a base fluid with nano-composite particles may serve to boost the capacities of thermal transduction devices and yield a higher heat transfer coefficient and Nusselt number (positive effect). It may also lead to higher pressure drop (negative impact). In order to explore the effects of a nanofluid precisely, the performance index (\(\varepsilon\)) should be a proper factor to clear up velocity and temperature values to serve in prepaid working fluids:

\[
\varepsilon = \frac{\Delta h/\Delta P}{\Delta h_{bf}/\Delta P_{bf}} = \frac{R_b}{R_P}
\]
(11)

\(R_b\) refers to the ratio between the heat transfer augmentation in the caused by the presence of the coolant (GNP-Pt hybrid nanofluids) and the base-fluid. On the other hand, \(R_P\) refers to the ratio concerned with the reduction of pressure by the hybrid nanofluid and the base-fluid. Provided that the flow is turbulent, Eq. (12) below may be used to estimate the pumping force in order to explore the aspects of energy efficiency [35]:

\[
W_{ef} = \left(\frac{\mu_{ef}}{\mu_{bf}}\right)^{0.25} \left(\frac{\rho_{ef}}{\rho_{bf}}\right)^2
\]
(12)

2.3. Validity of the experimental setup with water

To validate the data collected in practice, initial tests were performed using water in place of the working liquid. Fig. 2 compares the Nusselt number recorded for water and values obtained using theoretical correlations, such as Dittus-Boelter [29] and Petukhov [30]. As shown in Fig. 2, the data collected appears to be in tandem with theoretically obtained data using the empirical correlations of turbulent flow. To further elaborate, Dittus-Boelter relationship [29] was found to provide very similar Reynolds values (Re) to the ones measured here (all values < 15,000). When examining all Re values, Petukhov’s model [30] was found to approach the true values very closely. The test protocol was further validated as the average deviation in terms of the actual Nusselt values and the values computed using Petukhov relationships was found to be around 1.55%.

In addition, Fig. 3 shows the real values for the friction factor of distilled water as previously evaluated using Eq. (8) and the numerical data of Eqs. (9) and (10). Average deviations of 7.86% and 7.60% are obtained between experimental data and data from the two numerical
Table 1
Thermo-physical properties of water and GNP-Pt water based hybrid nanofluids at mean bulk temperature [26].

<table>
<thead>
<tr>
<th>Thermo-physical properties</th>
<th>Water</th>
<th>0.02%</th>
<th>0.06%</th>
<th>0.10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity, K (W/mK)</td>
<td>0.61</td>
<td>0.62</td>
<td>0.647</td>
<td>0.714</td>
</tr>
<tr>
<td>Viscosity, ( \mu ) (mPa·sec)</td>
<td>0.860420</td>
<td>0.986118</td>
<td>1.02667</td>
<td>1.04454</td>
</tr>
<tr>
<td>Density, ( \rho ) (kg/m3)</td>
<td>995.3</td>
<td>995.9</td>
<td>996.2</td>
<td>996.5</td>
</tr>
<tr>
<td>Specific heat capacity, ( C_p ) (J/g·K)</td>
<td>4.105</td>
<td>4.039</td>
<td>4.017</td>
<td>3.801</td>
</tr>
</tbody>
</table>

Table 1 lists the data collected at the mean bulk temperature for heat transfer, density, viscosity and specific heat capacity in all trials [26].

3. Results and discussion

3.1. Nusselt number and the convective heat transfer coefficient of GNP-Pt hybrid nanofluids

Different weight concentrations of GNP-Pt hybrid nanofluids were used in the heat transfer test rig. The results are plotted in Fig. 4. Eq. (4) has been used for calculation of the Nusselt number. The results confirmed the same trend with single-phase functionalized GNP nanofluids. Nusselt number improves as the nanoparticles’ weight fraction gets higher or as the Reynolds number is elevated. The increase in Nusselt number enhancement for functionalized GNP-Pt hybrid nanofluid is due to the thermo-physical characteristics of the nanocomposite.

Fig. 4. Nusselt number of functionalized GNP-Pt hybrid nanofluids as a function of Reynolds number for different weight concentrations.

Fig. 5. Heat transfer coefficient of functionalized GNP-Pt hybrid nanofluids as a function of Reynolds number for different weight concentrations.

Fig. 6. Friction factors of functionalized GNP-Pt hybrid nanofluids as a function of Reynolds number at different weight concentrations.

Fig. 7. Performance index of functionalized GNP-Pt hybrid nanofluids at different weight concentrations.

Fig. 8. Pumping power of functionalized GNP-Pt hybrid nanofluids at different weight concentrations.
nanoparticles.

Nusselt values were shown to increase to 4.58% and 6.35% in a nanofluid found at a 0.02% particle weight fraction. This accordingly reflected Reynolds values of 5000 and 17,500. On the other hand, Nusselt values reached 14.63% and 28.48% when the nanofluid was found at a concentration of 0.1 wt%. This implied that Nusselt number values reached 14.63% and 28.48% when the nano fluid found at a 0.02% particle weight fraction. This accordingly

Fig. 5 displays the heat transfer coefficient of the proposed samples trials at various load patterns of the nanocomposite. The maximum improvement of heat transfer coefficient was 49.16%, achieved at a Reynolds value of 17,500 for maximum weight concentration (0.1 wt %). The heat transfer enhancement for GNP–Pt nanofluid is due to the Brownian motion of the nanoparticle as well as better thermo-physical properties of the nanocomposite [2,36,37].

3.2. Friction factor of GNP-Pt hybrid nanofluids

Fig. 6 shows the friction factor of the functionalized GNP-Pt hybrid nanofluids at varying weight ratios of the nanocomposite. Friction factor increased to 10.98% at a 0.1% wt fraction of functionalized GNP-Pt hybrid nanofluid and a Reynolds number of 17,500. However, the improvement seen in terms of the friction factor as caused by the loading nanocomposite in the base fluid (water) was negligible when put against the elevation observed for the Nusselt number.

Fig. 7 indicates the performance index of GNP-Pt nanofluids for different Re numbers and weight concentrations. With the exception of the values seen when Re approached 5000, we observed that the performance index for all GNP-Pt nanofluids tested was higher than 1, regardless of the concentration. This revealed that GNP-Pt nanofluids could serve as suitable substitute working fluids heat exchangers with altered flow values. In addition, as the nanocomposite’s quantity became higher in the base fluid, the performance index rose. This suggested that the rheological factor played a greater role in heat transfer than before. Overall, our findings established an advantageous heat transfer impact, accompanied by a negative impact on pressure drop upon the utilization of our pre-synthesized nanofluids with varying concentrations and Re numbers. This confirmed that GNP-Pt nanofluids were highly efficient heat exchangers.

Optimizing pumping power has a major impact on the evaluation of energy efficiency in a thermal system, as it may serve to confirm the rheological capacity of a system. This can provide crucial information regarding the efficiency of the fluid when placed in a heat-exchanger device. Fig. 8 shows the pumping power in all trials at a multitude of wt ratios of the GNP-Pt nanofluids and the base-fluid. The readings taken at varying temperatures confirmed that no significant alteration of the pumping power was caused by the presence of the tested nanofluids, regardless of temperature and concentration. However, as illustrated in Fig. 8, a trivial pumping force rise (~ 7.2%) was detected with GNP-Pt weight concentration. This further established our preparation as a promising working fluid superior to other nanofluids [38].

4. Conclusion

GNP-Pt hybrid nanofluids were studied experimentally in terms of their forced convection heat transfer capabilities using a four-sided microchannel at a constant heat flux boundary condition. The effects of the nanocomposite’s load, temperature and Reynolds number were assessed in relation on the heat transfer and friction factor of heat exchanging working fluids. All samples showed significant enhancement as compared with the base fluids, with a maximum improvement of around 30% at the highest weight concentration and Reynolds number. Increments of the friction factor in the worst scenario were around 10%, with insignificant increases in the negative parameters as compared with the positive points. This confirmed the capacity of the prepared nanofluids to be promising working fluids for any type of thermal applications, including radiators and nuclear reactors.

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