Thermal Transport Phenomena of Graphene Oxide Nanofluids in Turbulent Pipe Flow

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Abstract: The aim of the present study is to investigate the thermal fluid flow transport phenomenon of graphene oxide (GO) nanofluids in the heated horizontal stainless steel circular tube that was subjected to a uniform heat flux at its outer surface. The heat transfer and the pressure drop within flowing base fluid (pure water) were measured and compared with the corresponding data from the correlations. Consideration is given to the effects of volume fraction of the nanoparticle on the heat transfer and the pressure drop within flowing base fluid. The heat transfer and the pressure drop within flowing base fluid were measured and compared with the corresponding data from the correlations. The convective heat transfer performance results show that the dispersed nanoparticles can always enhance the heat transfer coefficient of the base fluid, and the highest enhancement was obtained to be 181 % in the concentration of 0.2 vol.% of GO nanoparticles with Reynolds number 3000. The thermal conductivity enhancement depends strongly on the concentration of GO particles and increases with the increasing loading. It was also shown that the viscosity and pressure drop increase in accordance with an increase of the volume fraction.

Keywords: Nanofluid, Graphene Oxide Nanoparticles, Volume Fraction, Viscosity, Heat Transfer

1. Introduction

Processes of energy transport have been integrated in a wide range of areas, such as in industry, oil and gas, and electricity. In the past decades, ethylene glycol, water, and oil were used as conventional fluids in heat exchanger systems. However, improvement of these conventional heat transfer fluids, particularly thermal conductivity, has become more and more critical to the performance of energy systems. A new way to enhance thermal conductivity of the fluid is to suspend small solid particles in a fluid. Since publication of theoretical study by Maxwell [1], many studies for suspension including small solid particles were conducted. In particular, the problems such as stability, pressure loss and choke or erosion of flow path were disclosed in the case of millimeter or micrometer sized particles. The development of nanotechnology enables to produce nanoparticles which are the material less than 100 nm in diameter. Fluid including nanoparticles is called nanofluid, which is a term, proposed by Choi [2]. Torii S. [3] studied the convective heat transfer behavior of aqueous suspensions of nano-diamond particles flowing through a horizontal tube heated under constant heat flux condition. Teng T. et al. [4] examined the effect of particle size, temperature and weight fraction on the thermal conductivity ratio, and concluded that the weight fraction and temperature carry a proportional relationship with the thermal conductivity ratio and shrinkage of particle size enhance the thermal conductivity ratio of nanofluid. PrajapatiO. and Rajvanshi A. [5] investigated experimentally the turbulent flow forced convection heat transfer of nanofluid inside an annular tube with variable wall temperature, and The Nusselt numbers of nanofluid were obtained for various heat flux, Reynolds numbers and nanoparticle concentrations at atmospheric pressure. Xuan Y. and Li Q. [6] studied the single-phase flow and heat transfer performance of CuO nanofluid in tubes for turbulent flow and developing heat transfer correlation for the experimental data. Torii S. and Yoshino H. [7] performed experiments on turbulent heat transfer behaviors of two kinds of the nanofluids. In their study, Al2O3 and CuO were dispersed in ethylene glycol, and the experimental results showed that the Nusselt number of the dispersed fluids increases with increasing the volume fraction of the suspended solid particles and Reynolds number. Mehrali M. et al. [8] studied systematically the effect of particle mass concentration (0.025, 0.05, 0.075, and 0.1 wt.%), specific surface area and temperature on the stability and thermophysical properties of nanofluids containing graphene nanoparticles. Yu W. et al. [9] studied the effect of graphene nanosheets on thermal conductivity of the base fluid and estimated the thermal conductivity of graphene and graphene oxide. Ghozatloo A. et al. [10] showed study of convective heat transfer behavior of nanofluids through the shell and tube heat exchanger under laminar flow. Hajjar Z. et al. [11] measured thermal conductivity of graphene oxide nanofluids with different concentrations and temperature. The aim of the present paper is to study experimentally the effect of graphene oxide particles concentration on heat transfer enhancement, thermal conductivity, stability, viscosity, and pressure loss in the turbulent flow.

2. Experiment

2.1 Preparation of graphene oxide

Graphite fine powders (45 μm) was purchased from Wako pure chemical industries (Japan), concentrated sulfuric acids (H2SO4), sodium nitrate (NaNO3), potassium permanganate (KMnO4), hydrogen peroxide (30% H2O2), hydrochloric acid (5% HCL) and deionized water were used throughout the experiment. Graphene oxide (GO) was synthesized from natural graphite powder by a modified Hummers method [12]. Used 5g graphite powder and 2.5g sodium nitrate NaNO3,
were added to 115 ml concentrated sulfuric acid \( \text{H}_2\text{SO}_4 \) with mechanical stirring for 1 hr. Then, in a bottom-round flask (500 mL) with ice-water bath, 15 g potassium permanganate \( \text{KMnO}_4 \) was added slowly to keep the temperature of the suspension lower than 20 °C. With continuously stirring until a uniform liquid paste was formed (40 min.). Next, the flask was placed in a 35 °C water baths with stirring for 60 min.. At room temperature 230 ml DI water was added gradually, and rapid stirring was restarted to prevent effervescing (30 min.). Next, the flask was placed in a 90-95 °C oil bath and stirred the mixture for 30 min. without boiling, 400 ml and 50 ml of 30% \( \text{H}_2\text{O}_2 \) was added to the mixture with continuously stirring for 1 hr. if the synthesized succeed the colour change to yellow colour. 100 ml 5% HCL was added in succession. The suspension was then repeated washing and centrifugation (10000 rpm) to remove impurities. The centrifugation repeated by using distilled at least twelve times to remove the acids and improve pH value, and finally it was dried at 50 °C.

### 2.2 Nanofluids

A two steps method was used to prepare the graphene oxide nanofluids [13]. A graphene oxide nanoparticles was dispersed in pure water. The mixture was sonicated by using an ultrasonic washing machine (Tokyo, Fu-22H). The volume concentration \( \phi \) is estimated by equation (1). Four volume fractions were prepared for graphene oxide nanofluids 0.05%, 0.1%, 0.15% and 0.2% with different zeta potential and pH values (Table 1).

\[
\phi = \frac{\nu_p}{\nu_p + \nu_f}
\]

Where \( \nu_p \) is the volume of nanoparticles and \( \nu_f \) is the volume of base fluid.

<table>
<thead>
<tr>
<th>Volume Fraction [vol.%]</th>
<th>pH</th>
<th>Zeta potential [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>6.38</td>
<td>-23.1</td>
</tr>
<tr>
<td>0.1</td>
<td>4.95</td>
<td>-13.5</td>
</tr>
<tr>
<td>0.15</td>
<td>5.97</td>
<td>-19.5</td>
</tr>
<tr>
<td>0.2</td>
<td>5.62</td>
<td>-14.3</td>
</tr>
</tbody>
</table>

### 2.3 Experimental apparatus

Fig. 2 Schematic of Experimental Apparatus

The experimental system used for measuring the convective heat transfer characteristics of nanofluids flowing in a tube is shown schematically in Fig. 2. It consisted of a flow loop, a heat unit, a cooling part, and a measuring and control unit. The flow loop included a pump with a built-in flow meter, a collection tank and a test section. A straight stainless tube with 2000 mm length, 3.96 mm inner diameter and 0.17 mm thickness was used as the test section. Two electrodes for the direct electric current heating are installed at both ends. The power supply is adjustable. The test tube is surrounded by a thick thermal insulation material to obtain a constant heat flux condition along the test section. The twelve K-type thermocouples, which are welded on the outer surface of the test tube at axial position of 150 mm from the inlet of the test section to measure the local wall temperature along the heated surface of the tube, and the other thermocouples are inserted into the flow at the inlet and outlet of the test section to measure the bulk temperature of working fluid. In addition, the inlet and outlet was connected with a differential pressure instrument to measure the pressure drop at test section.
3. Results and Discussion

3.1 Thermal conductivity
Thermal conductivity is one of the most effective parameters which has significant effect on enhancement of heat transfer coefficient. The effective thermal conductivity of nanofluids is measured with the aid of a KD2 thermal property meter (Labcell Ltd, UK), which is based on the transient hot wire method. Here the thermal conductivity of the nanofluids and base liquid (pure water) are measured at 298 K.
For reference, the prediction which is obtained by the Hamilton and Crosser equation [14] (H-C equation) is superimposed in Fig. 3 as straight lines. This equation is a classical formula to predict thermal conductivity of solid-liquid mixture.

\[
\frac{K_{nf}}{K_f} = \frac{K_p + (n-1)K_f + (n-1)(K_p - K_f)\phi}{K_p + (n-1)K_f - (K_p - K_f)\phi}
\]

(2)

Where \(K_f\) is the thermal conductivity of the base fluid, \(K_p\) is the thermal conductivity of solid particles, \(K_{nf}\) is the thermal conductivity of nanofluid, \(\phi\) is the volume fraction of particles and \(n\) is the shape factor \((n = 3\) for spherical shape).
The effective thermal conductivity increases with increasing the volume fraction and the measured thermal conductivity of nanofluids are much higher than that of prediction. This is probably because these traditional models don’t account for various parameters like particle size, Brownian motion, nanolayering and effect of nanoparticles clustering, which are important to nanoparticles in nanofluids [15].

Therefore an increase of volume fraction of nanoparticle in nanofluid causes the reduction of flow property, and the high decrease in viscosity value of nanofluids is seen at shear rates less than 370 s\(^{-1}\).
The temperature is the main effective parameter on viscosity of nanofluids. The viscosity of nanofluids reduced with the raising of temperature at constant shear rate \((600\) s\(^{-1}\)) as shown in Fig. 5. Moreover, by rising the temperature, the nanoparticles are motivated more and create a more space for them. This is expected due to the weakening of the inter-particle and inter-molecular adhesion forces and similar trends are been observed for almost all other varieties of nanofluids [16].

\[\Delta p = f \frac{l \rho u^2}{D} \]

(3)

where \(l\) and \(D\) are the length and diameter of test tube, respectively, \(\rho\) is the fluid density, and \(U\) is the fluid velocity. The friction coefficient of pipe is given by the Blasius equation,

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

(4)

Fig. 3 Thermal conductivity versus volume fraction for two different nanofluids

3.2 Viscosity of nanofluids
The viscosity of nanofluids is measured with the use of a rotary viscometer (BROOKFIELD Co. DVII+ProCP). The measurement is carried out at 298 K for the nanofluids of different concentrations. The viscosity of GO nanofluids as a function of shear rate shown in Fig. 4. At given the viscosity of nanofluids increases with an increase in the particle concentration. From Figure 4 the viscosity of nanofluid increased rapidly with volume fraction.

Fig. 4 Nanofluids viscosity as function of shear rate

Fig. 5 Viscosity versus temperature at various temperatures and constant shear rates

3.3 Pressure drop of nanofluids
The experimental results show that the pressure drop and the friction factor depend on graphene oxide concentration and flow rate (Fig. 6). For reference, the pressure drop for base fluid which is predicted by Eq. (3), is superimposed as solid line.

\[\Delta p = f \frac{l \rho u^2}{D} \]

(3)
Figure 6 (a) and (b) shows good agreement exists between experimental data and theoretical model for pure water, the experimental results show that the pressure drop and friction factor depend on the graphene oxide particles concentration and flow rate. The pressure loss of the nanofluids is slightly increased compared with that of the pure fluid, because an increase in the friction loss is caused by suspension of nanoparticles in the pure fluid. Note that no substantial discrepancy for pressure loss appears in different nanofluids concentration. The pressure drop increases with an increase in flow rate. The nanofluid with the low volume fraction of suspended nanoparticles incurs almost no extra penalty of pump power.

3. Results and Discussion

3.1 Thermal conductivity

Thermal conductivity is one of the most effective properties of nanofluids. The effective thermal conductivity of nanofluids is measured with the aid of a KD2 thermal property meter (Labcell Ltd, UK), which is based on the transient hot wire method. Here the thermal conductivity of nanofluids is measured with the aid of a Hamilton and Crosser equation [14] (H-C equation) is as solid line.

\[ \frac{K_{nf}}{K_f} = \frac{1 + \phi V}{1 + \phi} \]  

where \( K_{nf} \) is the nanofluids thermal conductivity, \( K_f \) is the fluid thermal conductivity, \( \phi \) is the volume fraction of particles and \( n \) is the shape factor. The experimental results show that the pressure drop and the measured thermal conductivity increased rapidly with volume fraction.

<table>
<thead>
<tr>
<th>Volume Fraction</th>
<th>Thermal Conductivity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05% vol.</td>
<td>1.03</td>
</tr>
<tr>
<td>0.1% vol.</td>
<td>1.06</td>
</tr>
<tr>
<td>0.15% vol.</td>
<td>1.12</td>
</tr>
<tr>
<td>0.2% vol.</td>
<td>1.14</td>
</tr>
</tbody>
</table>

3.3 Pressure drop of nanofluids

The viscosity of nanofluids is measured with the use of a rotational viscometer. The friction coefficient of pipe is given by the Blasius equation,

\[ \frac{d\theta}{dr} = -2 \frac{u_1}{\theta} \]  

where \( u_1 \) is the velocity. The friction coefficient of pipe is given by the Blasius equation,

\[ f = \frac{8}{Re} \]  

where \( Re \) is the Reynolds number.

Figure 7 shows a comparison between the experimentally Nusselt number and theoretical equations

\[ Nu = \frac{(f/8)(Re-1000)Pr}{1.07+12.7\sqrt{f/8}Pr^{2/3}} \]  

where \( Pr \) is the Prandtl number. The Prandtl numbers and \( f \) is the friction factor.

\[ Nu = \frac{(f/8)Re Pr}{1.07+12.7\sqrt{f/8}Pr^{2/3}} \]  

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

Figure 7 shows a comparison between the experimentally Nusselt number and theoretical equations (8, 9 and 10). Very good agreement was achieved for experimental results for pure water compared with the prediction Gnielinski equation for turbulent flow. The Reynolds number is ranged from 3000 to 10000.

3.4 Convective heat transfer of pure water

The experiments were initially conducted for pure water to validate the reliability of the experimental setup for calculating the Nusselt number and the convective heat transfer coefficient and for providing a baseline to compare the GO nanofluid data. The experimental results for water at uniform heat flux conditions were compared with the results from the standard equations, such as the Gnielinski, Petukhov, and Dittus–Boelter equations for turbulent flow (Eqs. 8, 9 and 10 respectively) [3,16, 17].

\[ Nu = \frac{(f/8)(Re-1000)Pr}{1.07+12.7\sqrt{f/8}Pr^{2/3}} \]  

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3.4.2 Convective heat transfer of Nanofluids

Four volumetric concentrations are tested of graphene-oxide nanofluids, 0.05%, 0.1%, 0.15%, and 0.2% are tested in the present study.
Figure 8 shows the effect of nanoparticles concentration on the local heat transfer coefficient \( (h) \) and Nusselt number \( (Nu) \) at various Reynolds numbers. Figure 8 depicts the enhancement of heat transfer coefficient and Nusselt number with reference to base fluid (pure water). It can be seen that the heat transfer enhancement increases with increasing Reynolds number. This trend becomes larger with an increase in graphene oxide nanoparticles concentration. The convective heat transfer coefficient was increased up to 22%, 57%, 108% and 117% for GO particles concentrations of 0.05vol.%, 0.1vol.%, 0.15vol.% and 0.2vol.%, respectively, at \( Re=10000 \). Additionally, the Nusselt number \( (Nu) \) was increased up to 23%, 55%, 83% and 112% for the volume fractions of 0.05%, 0.1%, 0.15% and 0.2%, respectively, at \( Re=10000 \). The particle’s Brownian motion, the thermophysical properties (viscosity and thermal conductivity), and the specific surface area of nanoparticles were strongly affected in the convective heat transfer coefficient and Nusselt number [18]. Therefore, the higher concentration and Reynolds number increased the value of the convective heat transfer coefficient and Nusselt number. The enhanced heat convective performance of the nanofluid resulted from the higher thermal conductivity of the nanofluid and the disordered movement of the nanoparticles [18].

Previous studies claimed that the reasons for the heat transfer enhancement of the nanofluids included the mixing effects of the particles near the wall, particle migration, particle shape and rearrangement, the Brownian motion of the particles, the thermal conductivity enhancement, a reduction of the boundary layer thickness, and a delay in the boundary layer development [19, 20]. Figure 9 shows the enhancement of Nusselt number versus the volume fraction of the GO nanofluids at different Reynolds numbers. The largest enhancement of \( Nu \) which was 29%, 96%, 140%, and 181% for 0.05%, 0.1%, 0.15%, and 0.2vol.%, respectively, at \( Re=3000 \). Additionally, the enhancement increased with increase in particles concentration. The enhancement of \( Nu \) was reached to 100% for the volume concentrations of 0.1% and 0.15% at Reynolds number (3000–4000) and (5000–6000), respectively. For 0.05vol.% the enhancement less than 100% and for 0.2vol.% the enhancement more than 100% at all values of Reynolds number.

4. Conclusion
Experimental study has been performed to investigate the heat transfer characteristics and the pressure drop of a graphene oxide nanofluid in a horizontal tube with uniform heat flux. Graphene oxide was synthesized by the modified Hammers method. The following conclusions are obtained:

- Nanoparticle suspensions with high pH value are more stable than suspensions with low pH value.
- Adding graphene oxide nanoparticles to fluid can effectively increase the thermal conductivity ratio of the fluid, and the volume fraction carry a proportional relationship with the thermal conductivity ratio.
- The GO nanofluid viscosity was strongly dependent on the temperature. It decreased at high temperature.
- The relative viscosity of nanofluids increases with an increase in concentration of nanoparticles.
- The pressure drop of nanofluids is slightly increased with volume fraction compared to the base fluid. The pressure drop increased with flow rate.
- The suspended nanoparticles remarkably enhance heat transfer process and the nanofluid has larger heat transfer coefficient than base liquid (pure water) under the same Reynolds number.
For each concentration the convective heat transfer and Nusselt number increased with Reynolds number and volume concentration.

The largest enhancement of Nu which was 29%, 96%, 140%, and 181% for 0.05%, 0.1%, 0.15%, and 0.2 vol.%, respectively, at Re=3000.

**Nomenclature**

- $C_p$: specific heat [J/kgK]
- $h$: heat transfer coefficient [W/m2K]
- $q$: heat flux [W/m2]
- $k$: thermal conductivity [W/mK]
- $Nu$: Nusselt number
- $Pr$: Prandtl number
- $\rho$: density [kg/m3]
- $D$: pipe diameter [m]
- $A$: cross section area [m2]
- $S$: perimeter [m]
- $l$: tube length [m]
- $U$: fluid velocity [m/s]
- $T$: temperature [K]
- $\Delta p$: pressure drop [Pa]
- $f$: friction factor
- $n$: empirical shape factor
- $\phi$: particle volume fraction

**Subscripts**

- $f$: base fluid
- $nf$: nanofluid
- $p$: particles
- $w$: wall
- $x$: axial distance
- $in$: inlet

**References**


