Experimental investigation of Rheological behavior and pressure drop of aqueous suspensions of carbon nanotubes in a horizontal tube

Salma Halelfadl a,*, Thierry Maré a, Patrice Estellé b, Normah Mohd-Ghazali c

a Laboratoire de Génie Civil et de Génie Mécanique (LGCGM), INSA de Rennes, IUT Saint Malo, France
b LGCGM, INSA de Rennes/IUT Rennes, France
cFaculty of Mechanical Engineering, UTM, Johor Bahru, Malaysia

Abstract

A new engineering medium, called nanofluid, have attracted a wide range of researches on many processes in engineering applications. Many experimental and theoretical studies on viscosity of nanofluids are controversial and the shear rate dependent viscosity is frequently neglected. The aim of the present work is to investigate the effect of the rheological behavior of aqueous suspensions of carbon nanotubes on the friction factor and the pressure drop in a horizontal tube under laminar and turbulent flow. The particles weight concentration used here is 0.01%. The rheological behavior was measured for a range of temperature from 0°C to 40°C. The results showed that the nanofluids exhibit a shear thinning behavior at very low shear stress. The analysis results of the flow characteristics showed a non-Newtonian behavior under laminar flow and a Newtonian behavior under turbulent flow.

Keywords: Nanofluid; viscosity; shear-thinning; friction factor; pressure drop

Nomenclature

| Symbol | Definition |
|--------|------------|
| f      | friction coefficient |
| D      | diameter of horizontal tube (m) |
| g      | gravitational constant (m/s²) |
| Re     | Reynolds number |
| Q      | flow rate (m³/s) |
| L      | length of horizontal tube (m) |
| µ      | dynamic viscosity (Pa.s) |
| ε      | roughness (mm) |
| ϕ      | concentration (%) |
| ρ      | density (kg/m³) |
| ΔP     | pressure drops (Pa) |

Subscripts

| Symbol | Description |
|--------|-------------|
| mf     | nanofluid   |
| w      | water       |
| s      | surfactant  |
1. Introduction

Due to the global concern on energy conservation, the development and improvement of heat exchangers in many sectors (automobile, construction, electronics...) have today become a major issue in the industrial world. Therefore, the development of more efficient heat transfer fluids with higher thermal properties is considered urgent. Over the past decade, many researchers have investigated a new kind of heat transfer fluid called nanofluids to improve the heat transfer properties of liquids.

Nanofluids are fluid suspensions of nanometer-sized particles of metals, oxides, carbides, nitrides or nanotubes. They have attracted much attention because of their high thermal conductivity and thermal performances compared to base fluids [1-3]. Many researches have mostly focused on the thermal conductivity of these fluids [4-5]. However, the viscosity also deserves the same attention as thermal conductivity. In fact, viscosity describes the internal resistance of a fluid to flow and is an important property for all thermal applications involving fluids. In addition, the pumping power is related to the viscosity of a fluid. The addition of solid nanoparticles to a base fluid may lead to an increased viscosity and a significant pressure drop which can reduce the practical benefits of nanofluids in some industrial applications [6]. Numerous experimental and theoretical investigations have been carried out on viscosity and rheological behavior of nanofluids [7-12]. All these studies reported that viscosity of nanofluids increased with an increase of nanoparticles concentration and decreased with an increase of temperature. Compared to the thermal performances, the hydrodynamic behavior of nanofluids, especially for carbon nanotubes based nanofluids, has been rarely reported. In this present work, the focus is on an aqueous multi-walled carbon nanotubes based nanofluid at low weight concentration (0.01%). The effect of the viscosity and the hydrodynamics characteristics at ambient temperature is investigated in order to compare the experimental results on fraction factor between the nanofluid and pure water in a horizontal tube. Finally, the experimental data are analyzed using traditional equations for friction factor to evaluate the effect of the rheological behavior on nanofluid flow under laminar and turbulent conditions.

2. Experimental and data analysis

2.1. Nanofluids

An aqueous carbon nanotubes based nanofluid was provided by Nanocyl™ (Belgium). This suspension consists of thin multi-walled carbon nanotubes (carbon purity 90%) dispersed in a mixture of de-ionized water and surfactant from ultrasonication (fig. 1). The characteristics of the basic solution are summarized in Table1. De-ionized water was used to dilute the basic solution (1% wt) and prepare the suspension of 0.01% in mass concentration. The mixture is stirred with a mixer for 30min then left at rest and the process was repeated 24 hours later. The purpose of the mechanical stirring is to ensure a uniform dispersion of nanoparticles and prevent initial agglomerating of nanoparticles in the base fluid.

![Fig. 1. Tunneling Electron Microscopy (TEM) images of synthesized MWNTs by Nanocyl™](image)

Table I. Characteristics of CNT basic solution (1%wt)

| Supplier | Nanoparticles                  | Size         | \(\phi_{nf}(\%)\) | dispersant |
|----------|--------------------------------|--------------|-------------------|------------|
| Nanocyl  | Multi-Walled Carbon nanotubes  | D: 9-10nm    | 1%                | SDBS       |
|          |                                | L: 1.5\(\mu\)m |                   | \(\phi_{nf}(\%)=2\%\) |
2.2. Rheological behavior

The rheological measurements of nanofluid are performed using a stress controlled rheometer Malvern Kinexus Pro equipped with a cone and plate geometry. The cone diameter is 60mm and the cone angle is 1°. This leads to a measurement gap of 0.03mm. The temperature was controlled using a Peltier temperature control device located below the lower plate with an accuracy of 0.01 °C. The temperature is maintained constant 5 min before starting the test, which allows for the sample’s constant temperature condition and complies with standards. The experimental procedure involves applying a logarithmic stress ramp under steady-state conditions with maximum step duration of 180s. When a steady-state flow condition is achieved and maintained 10s, the shear rate is measured. The range of shear stress applied was between 0.01 and 0.5 Pa which ensures a steady flow for low shear rate and stability of the flow at high shear rate. During each test, the viscosity was measured as a function of temperature from 0 to 40°C. The tests were repeated to verify the reproducibility of the measurement and the suspensions stability with time.

Distilled water and standard oil were tested as calibration fluids at 20 °C to validate the experimental protocol used in this study. The results showed a Newtonian behavior for these fluids. Moreover, the dynamic viscosity measured at 20 °C is 1.03mPa.s for water and 1360mPa.s for oil, which represents a relative error less than 3% (water) and 4% (standard oil) in comparison with the theoretical values. These results validated the experimental protocol.

2.3. Experimental protocol: Hydrodynamic

A sketch of the horizontal flow that was used during the present study is illustrated in figure 2. A centrifugal pump (2) was sucking water from a reservoir (1) and the flow rate was controlled with a valve (3). The test section consists of a cylindrical PVC tube (5) of 333mm length, 19mm in inner diameter and 0.0015mm in roughness. Static pressure taps, at the test section are connected to piezometric tubes to assess the losses. The experimental setup contains a diaphragm for measuring the flow of water. The flow of nanofluid is obtained directly by measuring the time to fill a container of a known volume. The tests were performed on distillated water in laminar and turbulent flow conditions in order to validate the experimental protocol.

![Fig. 2. Experimental set up](image)

The friction coefficient is calculated from the two following models. Experimental model (see equation 1) is related to experimental results of linear pressure drops in the tube. Whereas, theoretical model is linked to classical equation for friction coefficient under laminar (equation 2) and turbulent flow (equation 3).

\[
f = \left( \frac{D}{L} \right) \frac{\Delta P}{\rho u^2 / 2}
\]

(1)

\[
f = \frac{64}{\text{Re}} \quad \text{Or} \quad f = \frac{16\pi D Q}{\rho}
\]

(2)

\[
\frac{1}{\sqrt{f}} = -2 \log_{10} \left( \frac{2.51}{\text{Re} \sqrt{f} \frac{\varepsilon}{3.71D}} \right)
\]

(3)
The density measurements were performed on Anton PAAR DMA vibrating tube densimeter connected to cell 602 with a high precision of $1.1 \times 10^{-5}$ g/cm$^3$. The density of the nanofluid measured at 20 °C is 999.603 kg/m$^3$.

Preliminary Measurements were performed on pure water in order to validate the experimental protocol. Figure 3 shows the evolution of the friction factor for experimental and theoretical data as a function of Reynolds number. The results show that the theoretical models (Eq. 2; 3) are in accordance with experimental measurements with a relative error of 5%. These results allowed the validation of the experimental protocol.

3. Results

3.1. Rheological behavior

Figure 4 shows the evolution of the apparent dynamic viscosity as a function of shear rate for a range of temperature from 0 to 40°C. The results showed that the nanofluid viscosity decreases with an increase of temperature. For low shear rate (less than 100 s$^{-1}$), the nanofluid behaves like a shear thinning fluid, as the apparent viscosity decreases with the increase of shear rate. For higher shear rates, the viscosity is independent of the applied shear rate and the nanofluid is Newtonian.

In the next section, we focus on the rheological behavior of nanofluid at low shear rates (0-200 s$^{-1}$) at 20 °C because the hydrodynamic study was carried out at room temperature (20 °C). Based on the results of Figure 8, the nanofluid is non-Newtonian for very low shear rate (less than 80-100 s$^{-1}$). The dynamic viscosity measured at high shear rate is $\mu_{nf} = 0.99915$ mPa.s (very close to that of pure water). However, we can note that nanofluid at 0.01 weight concentration have lower shear viscosity than water due to the lubricative effect of nanoparticles [14].
3.2. Hydrodynamic behavior

Figure 5 shows the evolution of pressure drop as a function of volumetric flow rate. We can observe that the nanofluid behave similarly as pure water with a slightly higher pressure drop. The results showed two different zones, low flow rates (less than 0.025 l/s) and high flow rates (greater than 0.038 l/s) where the pressure drops become much more important. These zones correspond respectively to laminar and turbulent flow. It is observed from figure 5 that at low flow rates, the pressure drops of the nanofluid are larger than the ones of distilled water. As the flow rate increases, the pressure drops of both nanofluids and the distilled water become almost the same.

![Fig. 5. Linear pressure drops of CNT/water and distillate water](image)

Figure 6 reports the evolution of the experimental and theoretical friction coefficient of the nanofluid with the flow rate. The experimental friction coefficient was obtained based on the results of Figure 4 and using equation 1. The theoretical coefficient is obtained by assuming that the nanofluid behave as a Newtonian fluid (Eq. 2 and Eq. 3) and applying the value of the viscosity measured previously ($\mu_{nf} = 0.000956$ Pa.s). At low flow rate, the experimental results are different from the theoretical model. This is because, as seen in figure 4, the rheological behaviour of the nanofluid is non-Newtonian at very low shear rate. As the flow rate increases, contrary to this, the difference between the experimental and the theoretical results become very small and the nanofluid behaves as a Newtonian fluid. This shows that the Newtonian model is not valid for low flow rate and that the viscosity is dependent on the applied flow (at low shear rate).

![Fig. 6. Experimental and theoretical friction factor of CNT/water](image)
4. Conclusion

In this work, we studied the rheological behaviour of a nanofluid based on carbon nanotubes dispersed in water with a weight concentration of 0.01% as a function of temperature and shear rate. The nanofluid behaves as a Newtonian for high shear rates (greater than 100s⁻¹). At a low shear rate, the nanofluid is non-Newtonian. We also studied the hydrodynamic behaviour of the nanofluid in a horizontal cylindrical pipe. The results have shown that the evolution of the experimental friction factor does not follow the classical model of Newtonian fluids for low flow rate. This can be explained by the rheological behaviour of nanofluid at very low and at high shear rates.

Section headings should be left justified, with the first letter capitalized and numbered consecutively, starting with the Introduction. Sub-section headings should be in capital and lower-case italic letters, numbered 1.1, 1.2, etc, and left justified, with second and subsequent lines indented. You may need to insert a page break to keep a heading with its text.

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