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An experimental study on the pressure drop of nanofluids containing carbon nanotubes in a horizontal tube

Gwon Hyun Ko [a], Kyoungyoon Heo [a], Kyoungjun Lee [a], Dae Seong Kim [a], Chongyoup Kim [b], Yangsoo Sohn [b], Mansoo Choi [a,*]

[a] National CRI Center for Nano Particle Control, Institute of Advanced Machinery and Design, School of Mechanical and Aerospace Engineering, Seoul National University, San 56-1, Shinlim-dong, Gwanak-gu, Seoul 151-742, Republic of Korea
[b] Department of Chemical and Biological Engineering, Korea University, Anam-dong, Seongbuk-Gu, Seoul 136-701, Republic of Korea

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Abstract

This article reports an experimental study on the flow characteristics of the aqueous suspensions of carbon nanotubes (CNTs). Stable nanotube suspensions were made for pressure drop measurements by two different methods. One of them is to disperse nanotubes using a surfactant, and the other is to introduce oxygen-containing functional groups on the CNT surfaces by acid treatment. The pressure drops in a horizontal tube and viscosities of nanofluids were measured and the effects of CNT loading and different preparation methods were investigated. Viscosity measurements show that both CNT nanofluids prepared by two methods are shear thinning fluids and at the same volume fraction, the nanofluids prepared by the acid treatment have much smaller viscosity than the ones made with surfactant. Under laminar flow conditions, the friction factor of CNT nanofluids stabilized by adding surfactant is much larger than that of CNT nanofluids prepared by acid treatment, and both nanofluids show larger friction factors than distilled water. In contrast to this, under turbulent flow conditions, the friction factors of both nanofluids become similar to that of the base fluids as the flow rate increases. It is also shown that as CNT loading is increased, laminar regime of nanofluids has been extended to further higher flow rates, therefore, nanofluids could have low friction factors than pure water flows at certain range of flow rates.

Keywords: Nanofluids; Shear thinning; Friction factor

1. Introduction

Nanofluids are liquid suspensions containing nanometer-sized particles and have recently been demonstrated to have great potential for improving the heat transfer properties of liquids [1–3]. A great deal of research has been performed to enhance the thermal performance of conventional heat transfer fluids by dispersing solid particles [4,5]. Substantially increased thermal conductivities of the nanofluids containing a small amount of metal, like Cu, or nonmetal, like SiC, Al_2O_3, and CuO nanoparticles have been reported [1–3].

In addition, carbon nanotubes (CNTs) have attracted much attention because of their unique structure and remarkable mechanical and electrical properties [6,7]. Large quantities of CNTs can now be produced by either arc discharge or thermal decomposition of hydrocarbon vapor, which provides the possibility to utilize CNTs in large scale. Recent studies reveal that CNTs have unusually high thermal conductivity [8–10]. It can be expected that the suspensions containing CNTs would have enhanced thermal conductivity and their improved thermal performance would be applied to energy systems. Choi et al. [11] reported anomalously high thermal conductivity of carbon nanotube suspensions in synthetic poly (α-olefin) oil. They reported 160% enhancement of the thermal conductivity when 1.0% CNTs is added. Xie et al. [12]

* Corresponding author. Tel.: +82 2 880 7128; fax: +82 2 878 2465.
E-mail address: mchoi@snu.ac.kr (M. Choi).

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presented 10–20% enhancement of effective thermal conductivities of CNT suspensions in distilled water and ethylene glycol. In the study, a chemical treatment utilizing acid mixture was employed to ensure well-dispersed aqueous suspensions by forming hydrophilic functional groups on the surfaces of the CNTs. Several other studies also reported the enhancement of thermal conductivity of CNT nanofluids [13–15]. Ding et al. [16] measured the convective heat transfer coefficient of aqueous suspensions of CNTs in a horizontal tube and reported that for nanofluids containing 0.5 wt% CNTs, its enhancement rate to water was over 350% at $Re = 800$. Compared to numerous researches on the thermal performance, the flow characteristics of nanofluids especially for CNT nanofluids have been rarely reported. The viscosity change due to the addition of solid particles may cause the increase in the friction drag, affecting the overall efficiency of the energy systems. For further understanding of the performance of nanofluids as a heat transfer medium, studies should be done for flow characteristics of nanofluids both in laminar and turbulent regimes.

In the present study, we investigate the flow characteristics of the aqueous suspensions of multi-walled carbon nanotubes. Two different methods are used to prepare stable nanotubes suspensions. One of them is to disperse nanotubes using a surfactant, and the other is to introduce oxygen-containing functional groups on the CNT surfaces by acid treatment. The pressure drops in the horizontal tube and viscosity variation for different shear rates are measured and the effects of CNT loading and different preparation method are investigated.

2. Experimental details

2.1. Nanofluids preparation

Distilled water (DW) and multi-walled carbon nanotubes were used to produce nanofluids. CNTs were provided by Iljin Nanotech Co. LTD. (Seoul, Korea). The CNTs were produced by chemical vapor deposition method. It is well-known that CNTs are hydrophobic, which are prone to aggregation and precipitation in water. Two different methods were adopted for producing stable CNT nanofluids. One was to use a surfactant, and sodium dodecyl sulfate (SDS) was adopted as a surfactant in this study. At first, SDS was dissolved in DW at the rate of 1.0 wt% and then the mixture of CNTs and SDS solution was sonicated to make well-dispersed and homogenous suspensions. The other method, which was utilized in our previous study [12], was to attach hydrophilic functional group onto the surfaces of CNTs. Nitric/sulfuric acid mixture was used to modify the surfaces of CNTs. In a typical treatment of the present work, 1 g of CNTs and 40 ml acid mixture were boiled and refluxed for 1 h. Then, the sample was diluted by distilled water, filtered, and washed repeatedly till the washings show no acidity. The cleaned CNTs were collected and dried at 150 °C to remove the attached water. Treated CNTs (TCNT) powders were added into DW in a mixing container. The TCNT/DW mixture was subjected to intensive sonication for producing well-dispersed and homogenous suspensions [12]. For convenience, in the present paper, CNT nanofluids produced by surfactant and acid treatment are referred to as the PCNT nanofluids (the pristine CNT nanofluids) and the TCNT nanofluids (the treated CNT nanofluids), respectively. Both nanofluids were maintained stable even after two months [12].

2.2. Measurements of viscosity and pressure drop

The viscosity was measured by using AR2000 viscometer (TA Instrument). The measurements were done on two nanofluids of different CNT concentrations at different shear rates between 0.01 and 100 s^{-1}.

Flow loop used for the pressure drop measurements is shown schematically in Fig. 1. Flow was provided by a magnetic chemical pump, whose pumping power was controlled by a digital inverter (VFD037 of Delta Co. LTD.). The flow rate was measured by using Ultramass MK-2 flowmeter (Oval Co.). A stainless-steel tube with 4 m length

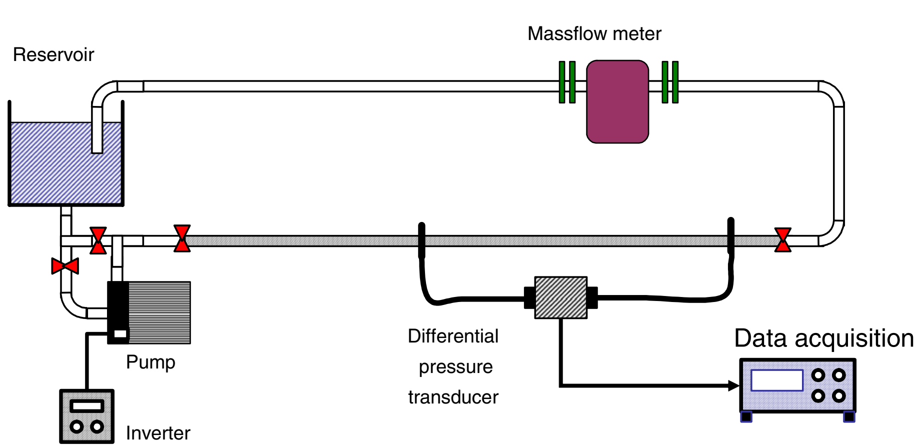

Fig. 1. Schematic diagram of the experimental apparatus for measuring the pressure drop in the horizontal tubes.

and 10.7 mm inner diameter was used as a test section. The first pressure tap was located at the 130-diameters downstream from the test section inlet, and the distance between two pressure taps is 2 m. The pressure drop between two pressure taps was measured by differential pressure transducers (Model 230 of Setra systems). From the measurement of pressure drop, the friction factor was calculated by the following definition;

$$f = \left(\frac{D}{L}\right)\frac{\Delta p}{\rho u^2/2} \tag{1}$$

where f represents the friction factor, ΔP is the pressure drop, D and L are respectively the inner diameter of tube and the distance between two pressure taps, and u is the mean velocity. The following relationships [17] for the friction factor of pure water were compared with nanofluids cases.

$$f = 64/Re \quad \text{(for laminar flow)}, \tag{2}$$

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{2.51}{Re\sqrt{f}}\right) \quad \text{(for turbulent flow in a smooth pipe)}. \tag{3}$$

3. Results and discussion

3.1. Viscosity of CNT nanofluids

Fig. 2 represents the viscosities of CNT nanofluids as a function of shear rate. A clear shear thinning behaviors are seen for both CNT nanofluids. At a given shear rate, the viscosity of PCNT nanofluids increases with increasing CNT volume fraction. Ding et al. [16] and Xu et al. [19] also observed the shear thinning behaviors of the CNT nanofluids and the carbon nanofiber suspensions, respectively. The non-Newtonian characteristics are frequently observed for the polymer solutions. In rheology, it is well-known that in the polymer solutions flow, the thread-like structured polymers, which are initially entangled complexly, are rearranged along the flow direction under the shear stress, and consequently the viscosity of solution decreases with shear rate [20]. In addition, recent studies [21,22] reported the morphological and physical similarity between polymers and CNTs, which also have the long-thread structure. Considering the structural similarity between polymers and CNTs, it is thought that the non-Newtonian behaviors of CNT nanofluids could occur from the rearrangement of CNTs under the shear stress. In other words, the CNTs in nanofluids are entangled and cause the highly viscous behaviors of nanofluids at rest or under weak shear stress. When the shear stress becomes strong, contrary to this, they are arranged along the flow direction and the viscosity of nanofluids is reduced. This flow-induced alignment of CNT was utilized to make macroscopic fibers and ribbons of CNTs [23] and a self-assembled bulk solid of CNTs [18]. Flow-induced alignment of CNTs was also studied in a polymer melt [24]. A comparison of viscosities between PCNT and TCNT nanofluids of 1400 ppm CNT loadings shows that the viscosity variations of TCNT nanofluids are much smaller than those of PCNT nanofluids. During the process for producing TCNTs, the acid treatment seems to soften CNTs and make the nanotubes more flexible [18]. Fig. 3 shows the TEM image of carbon nanotubes extracted from two nanofluids. One may conclude that the nanotubes of TCNT nanofluids are more bent than those of PCNT nanofluids. This morphological change induced by the acid treatment may cause the difference of the macroscopic behaviors such as viscosity and pressure drop of TCNT nanofluids from PCNT nanofluids. The flexibility of TCNTs may reduce the friction drag even under the low shear rate conditions.

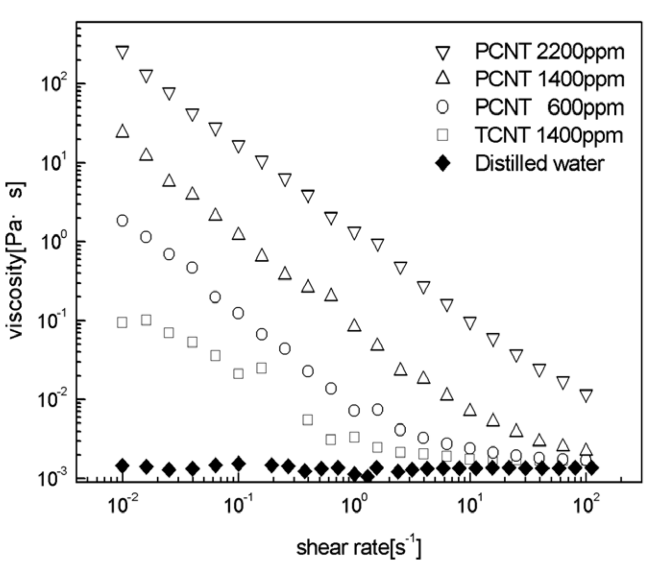

Fig. 2. Viscosity as a function of shear rate.

3.2. Pressure drop in the horizontal pipe

Fig. 4 compares the pressure drop of the PCNT and TCNT nanofluids with 1400 ppm CNT loadings in the horizontal tube with that of the distilled water. At low flow rates, the pressure drops of PCNT nanofluids are much larger than those of TCNT nanofluids and distilled water, but the difference between TCNT nanofluids and distilled water is small. This is because, as seen in Fig. 2, the rise in the viscosity of TCNT nanofluids is small compared to PCNT nanofluids at the same volume fraction and at the same shear rate. As the flow rate increases, contrary to this, the pressure drops of both nanofluids become almost the same as that of distilled water. The viscosity of nanofluids decreases with the shear rate and thus, the difference of pressure drop between nanofluids and distilled water also decreases.

Fig. 5 shows the friction factor of TCNT and PCNT nanofluids as a function of dimensionless flow rate, $Q^* = \frac{4Q}{\pi D \nu_0}$, where dynamic viscosity of water was used for all CNT nanofluids. In the case of pure water, the dimensionless flow rate becomes simply Reynolds number. As

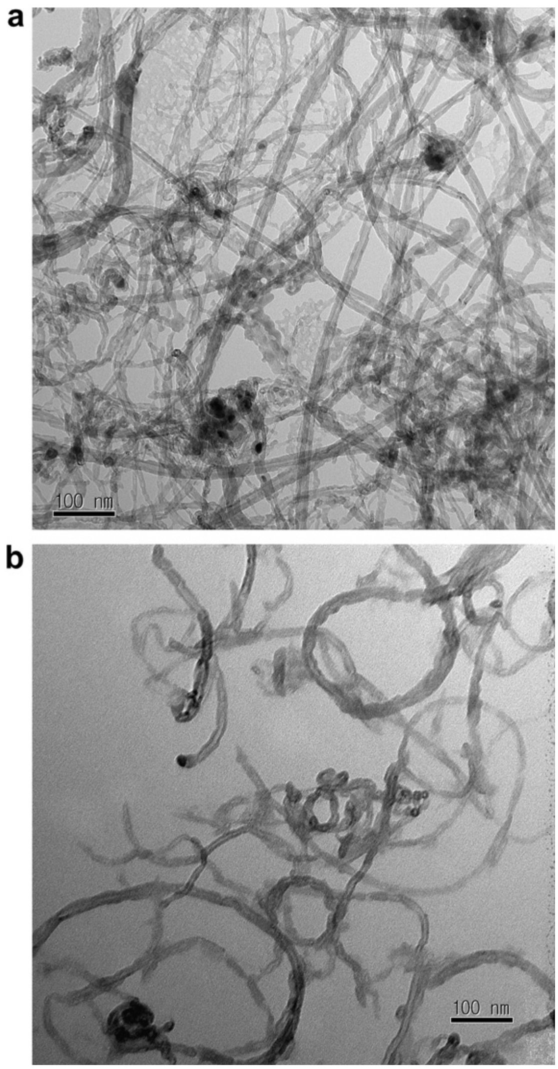

Fig. 3. TEM images of CNTs sampled from (a) PCNT nanofluids and (b) TCNT nanofluids at 50 ppm CNT concentration.

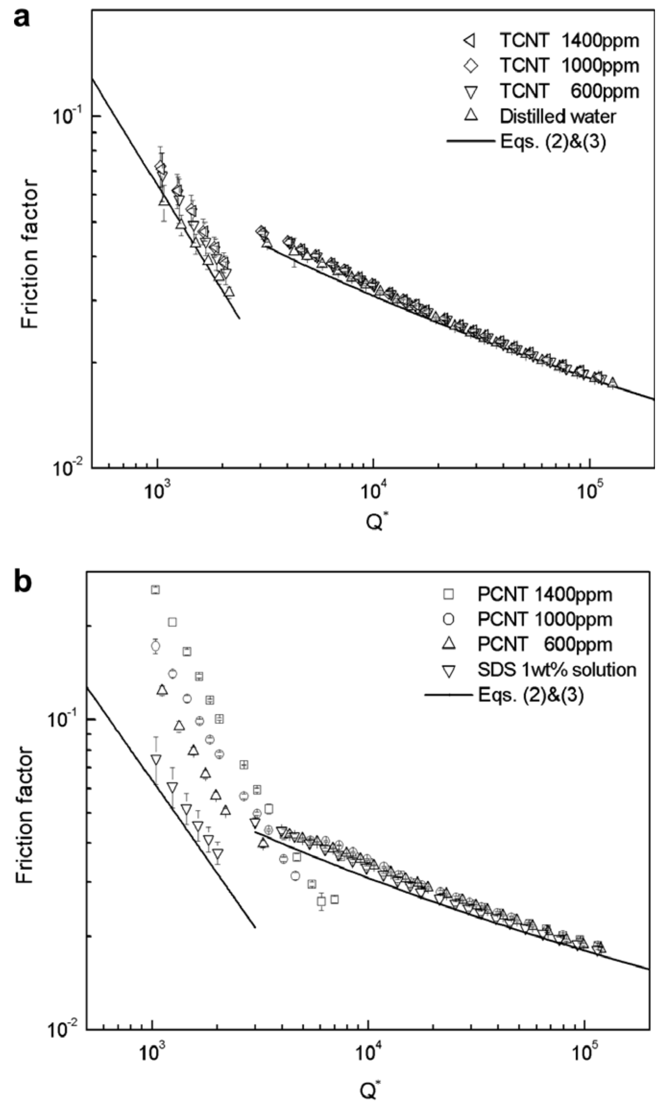

Fig. 5. Friction factor as a function of dimensionless flow rate.

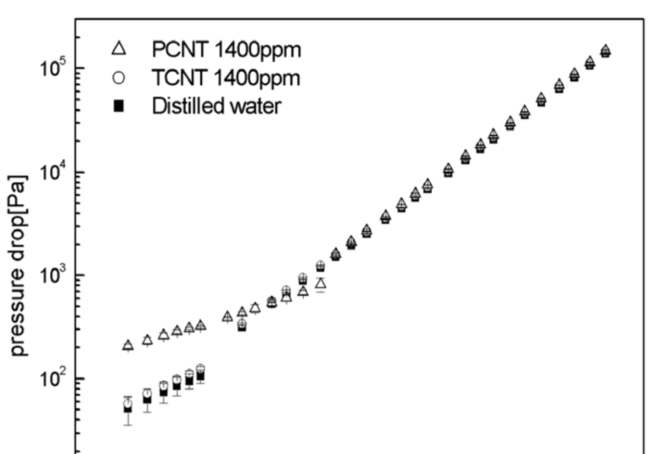

Fig. 4. Comparison of pressure drop with flow rate among the distilled water, PCNT and TCNT nanofluids of 1400 ppm CNT loadings.

seen in Fig. 5a, the friction factors of DW follow the general relationships (Eqs. (2) and (3)) of Newtonian fluids, indicating the validation of the experimental setup used in the present study. While some increases in the friction factor are shown for the TCNT nanofluids under the laminar flow conditions, friction factors become similar to DW under the turbulent flow conditions. Contrary to this, Fig. 5b for the PCNT nanofluids shows the significant deviation from the general relationship of pure water case in the laminar regime. Fig. 5b also included the friction factor of SDS solution only without CNTs for comparison. SDS solution exhibits mildly increased friction factors than distilled water due to a small increase of viscosity when added in water. The friction factors increase dramatically with the CNT concentration under the laminar condition. At the 1400 ppm (0.14 vol%) of CNT volume fraction and 2000 of dimensionless flow rate, the friction factor of PCNT nanofluids is about 2.7 times that of TCNT nanofluids. This is due to the significant increase in viscosity of PCNT nanofluids shown in Fig. 2. In laminar regime, viscosity variation with shear rate was well fitted by Sisko equation [20],

$$\eta = \eta_{\infty} + k\dot{\gamma}^{n-1}, \quad (4)$$

and the corresponding friction factor increase was in agreement with data. This means that in spite of the thermal conductivity enhancement, the overall efficiency of the heat transfer system using PCNT nanofluids may be reduced because of the increase in friction drag. On the other hand, under the turbulent flow conditions, the friction factors of both PCNT and TCNT nanofluids become similar to DW case. It is because the viscosity of PCNT nanofluids decreases at high shear rate due to its shear thinning effect, more fundamentally, alignment of nanotubes at high shear rates [18,23,24]. It is also shown in Fig. 5b that as CNT loading is increased, laminar regime of PCNT nanofluids has been extended to further higher flow rates than pure water case, therefore, nanofluids could have low friction factors than pure water flows at certain range of flow rates.

4. Conclusions

The present study measured the viscosity and the pressure drop of the CNT nanofluids flowing through the horizontal tube and investigated the effects of CNT concentrations and preparation methods. Two different methods were used to prepare stable nanotube suspensions. The first one was to disperse nanotubes by using surfactant; the second one was to introduce oxygen-containing functional groups on the nanotube surfaces by the acid treatment. Both PCNT and TCNT nanofluids showed the characteristics of shear thinning fluids, for which viscosity increases with decreasing shear rate. Especially, for PCNT nanofluids, the increase in the viscosities at low shear rates was much larger compared to TCNT nanofluids, and this causes the significant increase in pressure drops under the laminar flow condition. At the turbulent flow conditions, however, the pressure drops of both nanofluids presented similar values to those of the base fluid due to the shear thinning nature of CNT nanofluids. It was also shown that laminar regime of PCNT nanofluids has been extended to further higher flow rates than pure water case, therefore, nanofluids could have low friction factors than pure water flows at certain range of flow rates.

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