Thermochimica Acta 556 (2013) 47–53

Contents lists available at SciVerse ScienceDirect

Thermochimica Acta

journal homepage: www.elsevier.com/locate/tca

Experimental study on the characteristics of thermal conductivity and shear viscosity of viscoelastic-fluid-based nanofluids containing multiwalled carbon nanotubes

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ARTICLE INFO

Article history:
Received 17 October 2012
Received in revised form 14 January 2013
Accepted 21 January 2013
Available online 8 February 2013

Keywords:
Viscoelastic-fluid-based nanofluids
Thermal conductivity
Viscosity
Carbon nanotubes
Surfactant solution

ABSTRACT

In order to obtain a novel thermo-fluid with both turbulent drag reducing and heat transfer enhancement (compared with drag-reduced flow) abilities, we have prepared a viscoelastic-fluid-based nanofluid (VFBN) using viscoelastic aqueous solution of cetyltrimethyl ammonium chloride/sodium salicylate as base fluid and multiwalled carbon nanotubes (MWCNTs) as nanoparticles. The thermal conductivity and shear viscosity of the prepared VFBN with various particle volume fractions, temperatures and concentrations of the base fluid were then experimentally investigated. The results show that thermal conductivities of the tested VFBNs are significantly higher than that of the corresponding base fluid and increase with increasing particle volume fraction and fluid temperature, demonstrating potentials in heat transfer enhancement. A modified Li–Qu–Feng model (Y.H. Li, W. Qu, J.C. Feng, Chinese Phys. Lett. 25 (2008) 3319–3322), which includes the effect of liquid layering, particle clustering, particle shape factor, Brownian motion and viscosity of base fluid, is proposed in the present paper to predict thermal conductivity of VFBNs containing MWCNTs. The results predicted by this modified Li–Qu–Feng model show excellent agreements with the measured data. The VFBN with MWCNTs shows a non-Newtonian fluid behavior in its shear viscosity, and its shear viscosity increases with the increase of particle volume fraction and decrease of temperature. It is expectable that the prepared VFBNs may also have drag-reducing ability in turbulent flows.

1. Introduction

Nanofluids have attracted numerous researchers in the field of heat transfer because of their unique characteristics of substantial high thermal conductivity and convective heat transfer efficiency. Since Choi [1] created the new term nanofluids, which represents the mixtures of nanomaterials and traditional heat transfer fluids (liquids), lots of studies have been performed on the thermal performance of nanofluids, see, e.g., Özerinç et al. [2], Das and Choi [3] and Kleinstreuer and Feng [4]. It has been shown that adding small amount of nanoparticles, like Al_2O_3, Cu and CuO into conventional heat transfer media (water, ethylene glycol, oil and so forth) can significantly increase the thermal conductivity of the base fluids.

Carbon nanotubes (CNTs) are fibrous tubes, and were initially observed by Iijima [5] two decades ago. For their unusual structure and remarkable mechanical and electrical properties, CNTs have been paid great attentions by related researchers. Recent studies indicate that nanofluids containing multiwalled CNTs (MWCNTs with anomalously high thermal conductivity as reported by Kim et al. [6]) have greatly improved thermal conductivity as compared with its base fluid and can be applied to heat transfer system. Choi et al. [7] reported the largest magnitude of effective thermal conductivity enhancement, about 160%, when 1.0 vol% (volume fraction) CNTs was added in synthetic poly oil. Xie et al. [8] obtained 19.6%, 12.7% and 7.0% thermal conductivity augmentation for 1.0 vol% CNTs dispersed in decene, ethylene glycol and distilled water, respectively. These studies suggest that nanofluids containing CNTs are excellent flow media and might be the next generation of heat transfer fluids from the viewpoint of thermal performance. However, if considering from the viewpoint of hydrodynamics, the addition of nanoparticles in the conventional fluid will aggravate the pressure drop in a pumping flow system due to the increased viscosity of nanofluids, e.g., as stated by Teng et al. [9]. This defect constrains the application area of nanofluids in heat transfer system.

On the other hand, there is another group of liquid flow media, namely turbulent drag-reducing fluids, firstly reported by Toms in 1949 [10]: when adding a tiny amount of polymers or some kind of surfactants into the Newtonian fluids (liquids), the frictional drag of turbulent flow can be greatly reduced.

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0040-6031/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tca.2013.01.023

The drag-reducing polymer or surfactant solution is usually viscoelastic fluid. For cationic surfactants, under proper conditions of surfactant/counterion chemical structures, ratios, concentrations and temperature, rod-like micelles can be formed in their aqueous solution. Exerted by a proper shear stress, the rod-like micelles form a network structure, and this microstructure imparts viscoelasticity to the solution, which is responsible for the occurrence of turbulent drag reduction (DR) [11]. Li et al. [12,13] investigated the turbulent DR mechanism and heat transfer characteristics in a heated turbulent flow of drag-reducing aqueous solution of cetyltrimethyl ammonium chloride/sodium salicylate (CTAC/NaSal). It was showed that heat transfer reduction (HTR) always occurs together with DR at the same order. Several attempts to enhance heat transfer of the turbulent drag-reducing flow by additives have been reported in the literature so far, e.g., by Li et al. [14] and Qi et al. [15]. Nevertheless, the problems associated with HTR are yet solved satisfactorily.

It is straightforward to conjecture that the combination of advantages of the abovementioned nanofluids and turbulent drag-reducing solutions might produce a novel thermohydrodynamic fluid. We have named this kind of novel fluid as viscoelastic-fluid-based nanofluid (VFBN) in a recently published paper [16], which can circumvent the drawbacks and strengthen the advantages of both nanofluids and viscoelastic fluid. In 2010, Liu and Liao [17] firstly reported their experimental studies on flow and heat transfer characteristics of drag-reducing fluid with addition of carbon nanotubes. The fluid they used was just a kind of VFBN. Their experimental results testified the similar turbulent drag reducing effects between flows of viscoelastic fluids and VFBN. Both fluids can greatly reduce the frictional resistance in their turbulent flows. In addition, VFBN can also significantly improve the heat transfer efficiency.

We have experimentally investigated the thermal conductivity and shear viscosity of VFBN with aqueous solution of CTAC/NaSal as the base fluid and containing Cu nanoparticles [16], and the characteristics of turbulent flow resistance and heat transfer of such VFBN in a round tube [18]. It was obtained that the thermal conductivity of this VFBN increases with increasing particle volume fraction and temperature (a maximum 29% increase of thermal conductivity for the tested VFBNs was obtained), and this VFBN behaves non-Newtonian characteristics in shear viscosity [16]; a synergetic effect of both viscoelasticity and nanoparticles expected for VFBN flow shows up, i.e. either that DR and heat transfer enhancement co-occur compared with water based nanofluid flow, or that DR and HTR co-occur but with HTR rate being smaller than DR rate (for viscoelastic base fluid only, HTR rate is larger than DR rate) [18].

The present study is one of the continuous efforts paid for exploring novel working fluids used in turbulent flows in order to obtain significant turbulent DR meanwhile enhance heat transfer for drag-reduced turbulent flows. Stable VFBNs with MWCNTs as nanoparticles and aqueous solution of CTAC/NaSal as the base fluid were produced for experimental studies. The thermal conductivities and shear viscosities of different VFBNs (with different base fluid concentrations and different volume fractions of MWCNT nanoparticles) were then investigated experimentally. The experimental results of thermophysical properties for these prepared VFBNs are detailed in this paper.

2. Experimental procedures

2.1. Preparation of VFBNs

Distilled water, CTAC, NaSal and MWCNTs were utilized in the present experiments to prepare VFBNs. The CNTs were produced by chemical vapor deposition method (Chengdu Organic Chemicals Co. Ltd., China). Their properties are shown in Table 1. As the chemical affinity between MWCNTs and polar solutions is weak, the MWCNTs cannot be directly dispersed into aqueous solutions. By acid treatment, the hydrophilic functional groups can be introduced to the MWCNTs surface [8], similar to attachment of carboxyl functional group to the tubes, which is the situation of the MWCNTs used in the present experiment.

Table 1
Property of MWCNTs used in the present experiment.

	MWCNT1	MWCNT2	MWCNT3
Density (g/cm^3)	~2.1	~2.1	~2.1
Thermal conductivity (W/(m K))	~3000	~3000	~3000
Specific heat (J/(kg K))	600	600	600
Length (μm)	10–30	10–30	0.5–2
Outer diameter (nm)	8	10–20	8
Inner diameter (nm)	2	5	2

A two-step (preparing base fluid at first, and then nanofluid) method is employed to prepare the viscoelastic-fluid-based MWCNTs nanofluids. Since CTAC/NaSal aqueous solution has shown an excellent turbulent drag reducing ability in our previous experimental studies [11–13], we still choose it as base fluid herein. Proper amount of CTAC and NaSal powder in 1:1 weight ratio was added into the distilled water. After mixing for about 8 h, a stable and well-dissolved aqueous solution of CTAC/NaSal was obtained. The prepared solution was put still for one night to release air bubbles in the fluid. The eventual base fluid consisted of CTAC/NaSal aqueous solution and dispersant TNDIS (Chengdu Organic Chemicals Co. Ltd., China). The addition of dispersant was to help the dispersion of nanoparticles in the base fluid and the adding amount was dependent on the MWCNTs volume fraction. To prepare VFBNs, proper amount of MWCNTs (corresponding to a planned volume fraction) was added into the base fluid (at a certain concentration). After strongly mixing for 1 h, a stable VFBN with suspensions of nanoparticles was obtained. In the present study, the mass concentrations of CTAC/NaSal aqueous solution were 0, 50, 200 and 1000 ppm (ppm – part per million), respectively. And each base fluid was mixed with 0.05, 0.2, 1.0, 1.6 and 3.5 vol% of MWCNTs, respectively.

2.2. Measurement of thermal conductivity

Transient hot-wire method (THWM) was employed to measure the thermal conductivities of the prepared VFBNs in the present experiment. THWM, which can avoid natural convection successfully and has excellent precision and fast response, is one of the convenient measurement techniques for thermal conductivities of gas and liquid.

Fig. 1 illustrates the measured thermal conductivities for distilled water at different temperatures by means of the THWM system (XIA-TC-THW-L01, Xi'an Xiatech Electronic Technology Co. Ltd., China). The measurement error was estimated to be within 1%. Hence, the precision and reliability of the applied THWM system were validated.

2.3. Measurement of shear viscosity

Shear viscosity is one of the most important physical properties of fluids for a thermohydrodynamic application system, which reflects the inherent resistance of a fluid to flow and determines the pumping power of heat transfer system. On the other hand, based on the variation trend of shear viscosity versus shear rate, the fluid nature, i.e. either Newtonian or non-Newtonian, is defined. Compared with the large amount of investigations on thermal performance, only a few available studies have covered