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Heat transfer and flow behaviour of aqueous suspensions of titanate nanotubes (nanofluids)

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Abstract

Titanate nanotubes of an aspect ratio of ~10 are synthesized, characterised and dispersed in water to form stable nanofluids containing 0.5, 1.0 and 2.5 wt.% of the nanotubes. Experiments are then carried out to investigate the effective thermal conductivity, rheological behaviour and forced convective heat transfer of the nanofluids. The results show a small thermal conductivity enhancement of ~3% at 25 °C and ~5% at 40 °C for the 2.5 wt.% nanofluid. The nanofluids are found to be non-Newtonian with obvious shear thinning behaviour with the shear viscosity decreasing with increasing shear rate at low shear rates. The shear viscosity approaches constant at a shear rate higher than ~100–1000 s^{-1} depending nanoparticle concentration. The high shear viscosity is found to be much higher than that predicted by the conventional viscosity models for dilute suspensions. Despite the small thermal conduction enhancement, an excellent enhancement is observed on the convective heat transfer coefficient, which is much higher than that of the thermal conductivity enhancement. In comparison with nanofluids containing spherical titania nanoparticles under similar conditions, the enhancement of both thermal conductivity and convective heat transfer coefficient of the titanate nanotube nanofluids is considerably higher indicating the important role of particle shape in the heat transfer enhancement. Possible mechanisms are also proposed for the observed enhancement of the convective heat transfer coefficient.

Keywords: Titanate nanotubes; Nanofluids; Effective thermal conductivity; Rheological behaviour; Convective heat transfer; Heat transfer enhancement

1. Introduction

Nanofluids are liquid suspensions of nanoparticles with at least one of their dimensions smaller than 100 nm. The concept of nanofluids was proposed approximately a decade ago by Choi [1] and have attracted considerable interest because of reports of great enhancement of heat transfer (e.g. [2,1], mass transfer [3], and wetting and spreading [4]. These enhanced properties could make nanofluids promising for a number of applications including thermal management, thermal therapy, microfluidics and novel detergent formulation, thus impact on various industrial sectors as diverse as chemical and process, transportation, electronics, medical, and energy and environment.

Due to potential advantages of nanofluids such as enhanced thermal conductivity, excellent stability and little penalty due to pressure drop increase and pipe wall abrasion experienced by suspensions of millimeter or micrometer particles, heat transfer work dominates the literature on nanofluids in the past decade; see for example Wang and Mujumdar [5] for a review to 2006. However, these published studies are mainly on the effective thermal conductivity of nanofluids under macroscopically static conditions [6–16], only a small number of studies investigated the convective heat transfer of nanofluids [1,2,9,17–24]. Even in these few studies, there are inconsistencies [17,16,25,5]. There is therefore an urgent need to obtain more quality experimental data to draw firm conclusions for the convective heat transfer of nanofluids. The work reported in this paper forms part of an effort to meet this need. Various aspects of heat

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transfer and flow behaviour of aqueous based titanate nanotube nanofluids are studied in this work including synthesis and characterisation of titanate nanotubes, formulation and characterisation of the aqueous based nanofluids in terms of particle size, thermal conductivity and rheological behaviour, and systematic experiments on the convective heat transfer of the nanofluids.

Titanate nanotubes are a new material and there have been no studies on the flow and heat transfer behaviour of titanate-based nanofluids. The material can present a good new model for study of convective heat transfer of nanofluids, having very different chemistry to what has been studied thus far in the literature. As will be shown later, titanate nanotubes have an aspect ratio (p) of around 10, where the aspect ratio is defined as $p = L/b$ with L and b the length and diameter of the particles. Thus titanate nanotubes also provide an excellent physical model for examining the effect of particle shape on the thermal and flow behaviour of nanofluids.

2. Experimental

2.1. Synthesis of titanate nanotubes and formulation of nanofluids

Titanate nanotubes were synthesized by using a method similar to that reported by Kasuga et al. [26]. The raw materials used for the synthesis included titanium dioxide (TiO_2), sodium hydroxide (NaOH), sulfuric acid (H_2SO_4), and hydrochloric acid (HCl). They were all purchased from Sigma-Aldrich and used without further purification.

The method of titanate nanotube synthesis was based on the alkali hydrothermal transformation. Typically, 20 g of TiO_2 was added to 300 ml 10 M NaOH solution and heated for 22 h at 140 °C. This resulted in the formation of a white powder. The powder was thoroughly washed with distilled water and 0.05 M H_2SO_4 in sequence. The resulting product was then vacuum-dried at 80 °C to give the dry titanate nanotube powder, which was in the form of agglomeration [27].

In order to produce stable nanofluids the powder sample of nanotubes has to be de-agglomerated, which requires the use of devices such as high shear homogenisers. Such mechanical treatments usually result in disintegration of nanotube agglomeration and shortening of nanotubes [27]. In this work, distilled water and dry titanate nanotubes were used to make nanofluids containing 0.5, 1.0 and 2.5 wt.% (0.12, 0.24 and 0.60 vol.%) nanotubes. The procedure of the preparation was similar to that reported by Ding et al. [23] and Wen and Ding [28]. To avoid complications due to the presence of dispersant/surfactant, the nanofluids were formulated at a pH value of 11 achieved by using sodium hydroxide. The value of pH has been selected to obtain a high surface charge on the titanate nanotube surface. To break nanotube bundles, a high shear homogeniser (Ultra-Turrax T25, IKA, Germany) was used to process the water-nanotube suspension. The mixer had a gap of 0.5 mm between the rotor and the stator, and the rotational speed of the rotor was adjustable. The highest speed of the rotor was ~24,000 rpm, which could provide a shear rate up to 40,000 s^{-1} and opportunities to break agglomeration. The titanate nanofluids made in this way were found to be stable for at least two weeks. Fig. 1 shows TEM and SEM images of the dispersed samples. It can be seen that most of the nanotubes are isolated having an external diameter of ca. 10 nm and a length of ca. 100 nm. A close inspection of Fig. 1 also shows the presence of some agglomeration.

A Malvern nanosizer was also used to measure the effective particle size of the suspensions. It was found that average particle size was around 260 nm. This is clearly larger than that reflected in the SEM image, suggesting the presence of agglomeration and particle shape effect. It should also be noted that the Malvern nanosizer assumes the spherical particles and measures the hydrodynamic diameter of the particles; hence the measured large particle size is somehow expected.

2.2. Measurements of the effective thermal conductivity and viscosity of nanofluids

The thermal conductivity was measured by using a KD2 thermal property meter (Labcell Ltd., UK), which is based on the transient hot wire method. The KD2 meter has a probe with

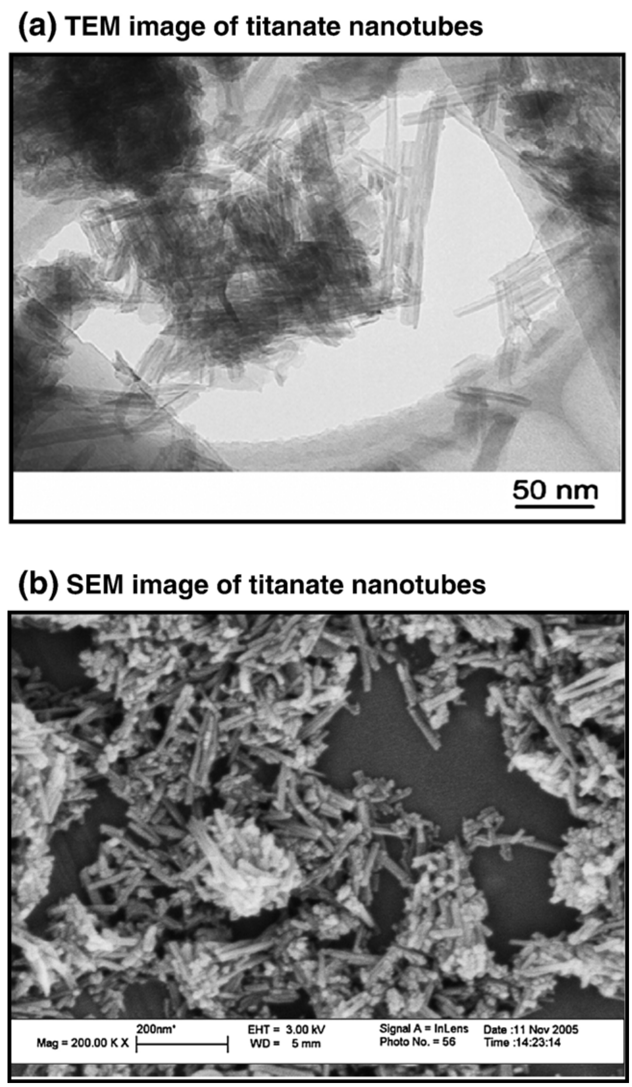

Fig. 1. TEM and SEM images of titanate nanotubes after dispersion.