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Thermal conductivity of nanofluids containing high aspect ratio fillers

Bangming Gu [a,*], Bo Hou [b], Zhangxian Lu [a], Zhengliang Wang [a], Shanfei Chen [a]

[a] Institute of Applied Physics, Zhejiang Wanli University, 8 Qianhu South Road, Ningbo 315101, China
[b] School of Physical Science and Technology, Soochow University, 1 Shizi Street, Suzhou 215006, China

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ABSTRACT

The effective thermal conductivity of three water based nanofluids (NFs) consisting of large aspect ratio fillers – carbon nanotubes (CNTs), silver nanowires, copper nanowires – were measured by transient hot wire method. The results show that silver nanofluid has the highest thermal conductivity compared with copper and CNTs nanofluids, while the latter two present almost the same thermal conductivity at the same volume fraction. The experiment indicates that particle shape has a substantial effect on the effective thermal conductivity of suspension and shape factor is one of the most important factors that leads to the large discrepancies among the experimental values of the thermal conductivities. Our results reveal that material with higher thermal conductivity is not a decisive factor and not always effective to improve the thermal transport properties of nanofluids.

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1. Introduction

In the past few decades, more than 300 research groups and companies are attracted in nanofluids research for its potential to enhance the heat transfer rate. Tremendous thermal conductivity (TC) enhancement has been observed [1,2]. These anomalous TC enhancements cannot be predicted by conventional Maxwell's theory [3] and Hamilton–Crosser (H–C) model [4]. Lots of mechanisms [5–16] were then proposed to explain the thermal transport properties of nanofluids. But these models show large discrepancies among each other, which greatly restricts their applicability. In fact, many of the experimental data, based on which the theoretical models were proposed, differ greatly from each other and remain non-reproducible. For example, Phuoc et al. [17] showed that the measured TC enhancements are independent of the base fluid viscosity, whereas in [18], Tsai et al. demonstrated that the viscosity of the carrier fluid does greatly affect the thermal conductivity of nanofluids. So what causes such a huge difference, or even contradictory experimental results? Even though there may be existing some unknown mechanisms affecting the thermal properties of nanofluids, why the results are still non-reproducible, when we use the same kind of nano-fillers and the same base fluids at the same volume fraction? In fact under such extensive research, most of the mechanisms behind the TC enhancement should have already been manifested. If all the experimental results in the literature are reliable, then all of the factors/mechanisms [5–16] will affect the TC enhancement value, and the discrepancies among the reported experimental results might be attributed to the fact that, in various situations, each factor plays a role at various levels. In other words, under condition A, the Brownian motion of particles plays the key factor; while under condition B, the particle-liquid thermal resistance is a decisive role; under condition C, the size and concentration of nanoparticles are the leading elements; whereas under condition D, the TC of the nanoparticles itself is of most importance. For instance, In [19,5] the authors illustrated that when a nanofluid contained nanoparticles of greater size (>40 nm), the volume fraction change had more obvious effects on the TC increment than the temperature change of fluid. In contrast, when a nanofluid contained nanoparticles of smaller size, the effects were the opposite, i.e. the factor of Brownian motion of the nanoparticles matters. Because of the agglomeration of nanoparticles, in [15] Hong et al. reported that the Fe nanofluids present higher TC enhancement than Cu nanofluids, although the TC of bulk Fe is lower than Cu, while in [12] the authors showed that nanoparticles with higher bulk TC also yielded higher TC enhancements.

Thus, in addition to clarifying whether there are undiscovered mechanisms, further researches should be done with a well planned variation of certain parameters, so that we can determine what causes the huge discrepancies among the published experimental results and which factor will play a decisive role in a certain case. Framed in this general background, the purpose of this paper is to figure out the role of the aspect ratio (the ratio of length to diameter).

The unusually high TC and aspect ratio make carbon nanotubes (CNTs) the best promising candidate material for thermally conductive composites. However, the TC of CNTs nanofluids are

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[*] Corresponding author. Tel.: +86 13777001038.
E-mail address: cgegbm@126.com (B. Gu).

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relatively low compared with expectations from the intrinsic TC of CNTs. Was it caused only by the interfacial resistance or accompanied by some other factors? Did the relatively high TC of CNTs nanofluids comparing with other nanofluids arise mainly from its intrinsic high TC or from its high aspect ratio? In this paper, silver and copper nanowires (NWs) nanofluids were then prepared to compare with CNTs nanofluids. All of the three fillers have large aspect ratio, but different thermal conductivities. Transient hot wire method was used to measure the TC of the nanofluids, the result of which may tell us which factor will be of more importance in this case.

2. Experimental detail

In this paper, the TC of four different nanofluid systems with different concentrations was investigated. Distilled water was used as the base fluid. The characteristics of the fillers, such as diameter and length, are displayed in Table 1. CNTs used in this study are the multi-walled carbon nanotubes (MWCNTs), made by chemical steam deposition with 95% purity, were provided by Zhejiang University, China. Copper nanowires and silver nanowires were both commercially purchased from Nanjing Xfnano Materials Tech Co., Ltd, China. The nanofillers were characterized using Scanning Electron Microscope (SEM).

All the nanofluids were prepared through the so-called two-step method (see [17,20] for details) and polyvinyl pyrrolidone (PVP) was adopted as the surfactant. The PVP has a molecular weight of 40,000, is of analytical grade and obtained from Shanghai Chemical Reagents Company. For all the samples, the nanofluids were ultrasonically oscillated at 50% amplitude using a 130 w, 20 kHz ultrasonic processor for 20 min and followed by 10 min stirring using a magnetic stirrer to obtain uniform dispersion of nanoparticles in the base fluids. The sonication was performed in an ice bath to maintain a constant temperature in the suspension.

Nanofluids with five concentrations: from 0.06% to 0.2% by volume were produced in this research. The rheological behavior is significant to nanofluids stability and flow behavior. If the benefits associated with heat transfer enhancement of nanofluids results in greater penalties in terms of pumping power and system reliability, it will be impractical for industrial application [21]. Therefore, only low concentration was prepared here because the nanofluids containing tube/rod-like nanoparticles (i.e. with high aspect ratio) will be very viscous and become “mud-like” at high concentrations, which makes it much less useful as a coolant or for lubrication applications [22].

Thermal conductivities of all the water-based nanofluids were measured by using a transient hot wire method reported elsewhere [23]. In this experiment, two platinum hot wires of diameter 50 μm were used in order to eliminate the end effect. A 1.5 μm thick insulation layer was coated on the wire surface to minimize the leakage of electrical current from the electrodes to the surrounding fluid. To keep temperature constant, the cells were immersed in a electro thermostat DHP3000 (Wanhua Laboratory Instrument, China), the temperature fluctuant of which is smaller than 0.5 °C. The hot wire serves as a heating element, through electrical resistance heating, and as a thermometer simultaneously. The same heating currents were applied to both wires to compensate the end effects. By measuring the temperature dependent change in the electrical resistance of the platinum wire, the thermal conductivity can be calculated from the relationship between the electrical and the thermal conductivity [23]. General rules for evaluating and expressing uncertainty in measurement, which can be followed at various levels of accuracy, have been established as the GUM method (Guide to the Expression of Uncertainty in Measurement) [24]. Uncertainty (U_f) in the measurement of a parameter ‘f’ is given by:

Table 1
Specification of the nanoparticles.

Item	Diameter (nm)	Length (μm)	TC (W/m K)	Purity (%)
CNTs-1	10–15	10–20	2000	>95
CNTs-2	10–15	0.6–3	2000	>95
Ag- NWs	60	20–30	429	>99.5
Cu- NWs	100–200	0.8–6	401	>96.5

$$U_f = \left[\sum_{j=1}^{N}\left(U_{Xj}\frac{\partial f}{\partial X_j}\right)^2\right]^{0.5}$$

where U_{Xj} is the uncertainty in the measurement of variable X_j. $\frac{\partial f}{\partial X_j}$ is called as sensitivity coefficient.

Based on the above GUM analysis, and also the experimental setup was calibrated by comparing the measured values of thermal conductivity for de-ionized water, and ethylene glycol against literature values, the uncertainty of the thermal conductivity enhancement were believed to within an uncertainty of 2.0%. The thermal conductivity of the fluid was measured after the nanofluid was settled for more than 30 min to eliminate the effects caused by oscillation. All the measurements were repeated at least five times to ascertain the accuracy of the experimental results.

3. Results and discussion

3.1. Stability of the nanofluids

The dispersion stability of nanofluids containing CNTs, Ag and Cu nanowires was determined by visual inspection. The nanofluids were placed in a see-through glass vessel and observed to determine if any precipitation had occurred. No settlements were observed during the first 400 h after nanofluids preparation, so the fraction of contained nanofillers remained unchanged.

Ultra Violet–Visible spectrophotometer (UV–Vis) spectrophotometer was also used to rank the relative stability and homogeneity of nanosuspension. UV–Vis measurements have been used to quantitatively characterize colloidal stability [25]. The CNTs, Ag and Cu based nanofluids were diluted and the peak absorbances of the three nanofluids are determined at very dilute suspension by scanning. As the concentration of suspension should have a linear relation with absorbance [25], UV–Vis measurements were carried out for three different dilute concentrations (0.005%, 0.01%, 0.02%) and were fitted to a linear relation to ascertain the accuracy of the results (not shown here). To check the relative stability, the supernatant concentrations will be measured by UV–Vis spectrophotometer and the relative concentrations were plotted against time which were shown in Fig. 1. Because the other two nanofluids exhibited almost the same tendency, Fig. 1 only depicts the colloidal stability of CNTs nanofluids. As we can seen from Fig. 1, relative concentration is maintained invariable compared with the initial concentration.

To confirm the dispersion stability of nanofluids, the thermal conductivities VS time were also investigated. The effective TC of the nanofluids was measured by transient hot wire method. Fig. 2(a)–(c) show the TC enhancement at room temperature (25 °C) with respect to time for Ag nanofluids, CNT-1 nanofluids and Cu nanofluids respectively. Each TC value in the figure is the average of five measurements and the data have a two-σ precision limit of ±2%. The three nanofluids are all with 0.2% volume fraction in Fig. 2. Similar trend was observed for all the nanofluids with other volume fractions. The ordinates is thermal conductivity enhancement ratio $\Delta\lambda/\lambda_0$, where $\Delta\lambda = \lambda_e - \lambda_0$. λ_e and λ_0 represent the effective thermal conductivities of the nanofluids and the base fluid respectively. It can be seen that the enhancement value was

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