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Effects of inclusion size on thermal conductivity and rheological behavior of ethylene glycol-based suspensions containing silver nanowires with various specific surface areas

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ABSTRACT

This work is concerned with the size effects of Ag nanowires on thermal conductivity and rheological behavior of EG-based suspensions. The influences of inclusion concentration and temperature on the thermophysical properties of specimens containing three types of Ag nanowires were also investigated. It was shown that the measured thermal conductivity of EG-based suspensions increased with the rising temperature and loading. Besides, the relative enhancement in thermal conductivity exhibited a linear relationship with respect to the specific surface area of Ag nanowires. A theoretical approach was developed to predict the effective thermal conductivity of suspensions containing nanowires by introducing liquid layer into account. The Ag nanowires/EG interface thermal resistances were extracted from the experimental results, which ranged from 2.0×10^8 to 5×10^8 m^2 K/W. Furthermore, a comparative study revealed the excellent performance of Ag nanowires used in present work on improving thermal conductivity compared with the reported studies. Finally, the presence of Ag nanowires with the highest aspect ratio (250) was concluded as the main explanation of a noticeable rise in dynamic viscosity and non-Brownian fluid behavior of EG-based suspensions at the highest loading (10 mg/mL).

1. Introduction

The long-term stable colloidal suspensions containing nanoscale inclusions (CuO, Al_2O_3, carbon nanotubes, etc.), coined as nanofluids, have been explored extensively as a novel family of engineered fluids [1]. It is proved that the advanced media are capable of offering remarkable high thermal diffusivity due to the size-related advantages of ultrafine inclusions and thus greatly enhance the convective and boiling heat transfer [2]. This characteristic of nanofluids sheds light on their great potentials in a host of industrial applications including power generation, electronics and cooling of nuclear reactors [3].

During the past decades, the effective thermal conductivity of nanofluids was concluded to be close related with a variety of factors, including the loading, size, dispersion of inclusions as well as temperature [4]. Several groups have noticed the significant influences of inclusion shape on the thermal conductivity of suspensions in the presence of nanoparticles such as SiC, TiO_2, Al_2O_3 and carbon nanomaterials [5–7]. These studies confirmed the benefits of nanoparticles to enhancing the thermal conductivity of base fluid, and discovered the increase was particularly pronounced for the samples containing one dimensional (1-D) ones. There are two possible reasons for this phenomenon. The first one is the rapid heat transport along the relatively larger distances in 1-D nanoparticles because of their lengths on the order of micrometers [6]. The other one is the large aspect ratios of 1-D nanoparticles that allow the formation of percolating structures to bring outstanding enhancement of thermal conductivity even at low concentrations [7]. Of the various highly-conductive 1-D nanoparticles available, carbon nanotubes (CNTs) have gained increasing attention due to their high thermal conductivity, chemical stability and low density [8–16]. Other 1-D nanoparticles such as Ag nanowires and Cu nanowires are also commonly involved for the purpose of thermal conductivity enhancement [7,17]. However, due to not considering the distinct geometrical properties of 1-D nanoparticles, the existing predictions that simplify the nanowires as spherical or cylindrical inclusions often underestimated the measured thermal conductivities [18,19]. As a

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Nomenclature

k	thermal conductivity, W/m K
d	diameter of nanowire, m
l	length of nanowire, m
f	volume fraction
t	thickness of liquid layer, m
R	interface thermal resistance, m^2 K/W
M	molecular weight, g/mol
N	Avogadro's constant, mol^{-1}
K	relative enhancement of thermal conductivity
C	mass/volume concentration, mg/mL

Greek symbols

a	Kapitza radius, m
β	geometrical coefficient
ρ	density, g/cm^3

Subscripts/superscript

11	transverse direction
33	longitudinal direction
eff	effective
m	liquid matrix
s	silver

consequence, more concerns need to pay for the integration of the inclusion size effects into the theoretical models based on a well-planned variation of certain parameters. Moreover, a better understanding of energy transport across the interface between inclusions and liquid matrix is critical for designing novel suspensions with high-performance.

Besides of the above-mentioned approaches to the size effects of 1-D nanoparticles on thermal conductivity enhancement, attention has also been paid to the rheological behavior of nanofluids [20]. The increasing viscosity of suspensions will aggravate the pressure drop in a pumping flow system and decrease the convective heat transfer coefficient, and therefore it is necessary to study the rheological behavior of base fluid after the addition of nanoparticles. Generally, it will be easier for 1-D nanoparticles with high aspect ratios to entangle and form bundles when added to liquid because of strong inter-tube van der Waals interactions [21]. Such character means the rheological behavior of base fluid in presence of 1-D nanoparticles deserves further in-depth studies.

This paper aims at investigating the size dependence of Ag nanowires on the thermal and rheological characteristics of EG-based nanofluids in experimental method. A modified model is presented to calculate the effective thermal conductivity of suspensions containing 1-D nanoparticles. Meanwhile, other essential variations that can affect the thermophysical properties of nanofluids, including loading of inclusion and temperature, are examined.

2. Theoretical

In predicting the thermal conductivity of composites containing non-spherical inclusions, the effective medium theory (EMT)-based Hamilton and Crosser (H–C) model [22] has been long used by introducing an empirical shape factor. It is noted that when considering spherical inclusions, the H–C model reduces to the original Maxwell's model [23]. H–C model demonstrates that the high shape factor of inclusions dispersed in base fluid contributes to better performance on thermal conductivity enhancement. However, the thermal conductivity enhancement of suspensions in presence of 1-D nanoparticles is theoretically intriguing because the measured values are still far underestimated by the prediction of H–C model [7]. A modified Maxwell–Garnet approximation was derived for the effective thermal conductivity of suspensions by taking inclusion size into account but found to cause an overestimated prediction [24]. Afterwards, considering the phonon scattering at the interface between inclusions and liquid matrix, Nan et al. [25] developed their model by incorporating the effect of the thermal interface resistance, expressed as:

$$\frac{k_{\text{eff}}}{k_{\text{m}}} = \frac{3 + f(\beta_{11} + \beta_{33})}{3 - f\beta_{11}} \tag{1}$$

$$\beta_{11} = \frac{2(k^{s}_{11} - k_{\text{m}})}{k^{s}_{11} + k_{\text{m}}} \tag{2}$$

$$\beta_{33} = k^{s}_{33}/k_{\text{m}} - 1 \tag{3}$$

where k_{eff} refers to the effective thermal conductivity of suspension. k_{m} is thermal conductivity of base fluid, and f denotes the loading (volume fraction) of inclusions. It should be noted that the Nan et al. model is applicable only if f is less than 0.01 in order to assure each nanowire isolates from each other. k^{s}_{11} and k^{s}_{33} are, respectively, the transverse and longitudinal equivalent thermal conductivities of inclusions, which were evaluated according to the observed sizes of nanowire as follows:

$$k^{s}_{11} = \frac{k_{\text{s}}}{1 + \frac{2\alpha}{d}\frac{k_{\text{s}}}{k_{\text{m}}}} \tag{4}$$

$$k^{s}_{33} = \frac{k_{\text{s}}}{1 + \frac{2\alpha}{l}\frac{k_{\text{s}}}{k_{\text{m}}}} \tag{5}$$

where d and l are the diameter and length of nanowire, respectively. k_{s} is the thermal conductivity of silver in this paper. α is a so-called Kapitza radius defined by

$$\alpha = Rk_{\text{m}} \tag{6}$$

where R denotes interface thermal resistance.

Furthermore, as well as interface thermal resistance, the formation of nanolayers [26] and microconvection due to Brownian motion [27] are commonly used to explain the unique heat conduction mechanisms in nanofluids. Several studies on the spherical nanoparticles drew the conclusion that the decrease of the inclusion size would lead to a growth in thermal conductivity enhancement. One main reason was the inclusions that are smaller in actual size travel more faster [28]. But unlike the nano-scale diameter of spherical inclusions, 1-D nanoparticles are generally a few tens of micrometers in length, so the Brownian motion of inclusions tends not to be a key mechanism governing their thermal behaviors especially at relatively low temperature evaluated. In contrast, the effects of the liquid layer between inclusion and base fluid should not be ignored for the 1-D nanoparticles that possess significantly large specific surface areas. According to the Langmuir theory of monolayer absorption of molecules, we assure the thickness of the liquid layer as [29]:

$$t = \frac{1}{\sqrt{3}}\left(\frac{4M}{\rho_{\text{m}}N}\right)^{1/3} \tag{7}$$

where M is the molecular weight of the liquid on inclusions, ρ_{m} is the density of base liquid, and N is Avogadro's constant (6.023×10^{23} mol^{-1}). Fig. 1 shows the schematic illustration of a nanowire unit coating with liquid layer. The thermal conductivity