International Journal of Heat and Mass Transfer 70 (2014) 421–429

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A novel method to evaluate dispersion stability of nanofluids

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ARTICLE INFO

Article history:
Received 29 July 2013
Received in revised form 9 November 2013
Accepted 11 November 2013
Available online 1 December 2013

Keywords:
Nanofluid
Nanoparticle
Hydrometer
Dispersion stability
Dynamic light scattering
Thermal conductivity

ABSTRACT

The thermal conductivity of nanofluids is known to be a function of the nanoparticle concentration and the particle size and is known to vary with time due to sedimentation and aggregation induced by particle–particle interaction. Therefore, it is crucial to measure the nanofluid thermal conductivity together with temporal variation of the volume fraction. However, researchers have reported only the estimation of the initial volume fraction based on the particle mass added to the base fluids and the primary particle size, which could be the crucial cause of the deviation between the thermal conductivity measurements from different research groups.

In this study, a new method is introduced to track the temporal changes of the particle volume fraction and size distribution, and the effects of the change of the nanofluid thermal conductivity are scrutinized. Five different nanofluids are generated: DI water/Al_2O_3, DI water/SiO_2, DI water/Ag, EG/Al_2O_3, and EG/ZnO. The particle volume fraction change is identified by monitoring the suspension density using a hydrometer, and the particle size distribution change is analyzed using the dynamic light scattering (DLS) method. The thermal conductivity of each of the nanofluids is measured using the transient hot-wire method. From the analysis of the data, the nanofluid thermal conductivity is found to be affected by the changes in concentration and the particle size distribution.

1. Introduction

Nanofluid is nanoparticle suspended fluid and is known for its remarkable thermal conductivity enhancement compared with the base fluid. Many research studies have been conducted regarding the thermal conductivity measurement technique and a broad range of related topics, including the thermal conductivity increase mechanism and several factors affecting the thermal conductivity of nanofluids, such as temperature, volume concentration, and dispersion stability.

Several researchers reported considerable thermal conductivity enhancement of over 20% with only a small particle fraction of 1–5% [1–4]. In addition, several works focused on the nanofluid thermal conductivity affected by the particle state in fluid. Lee et al. [2] and Wang et al. [5] reported that the thermal conductivity of a water-based CuO nanofluid increases linearly with the volume concentration. The thermal conductivity augmentation of the nanofluid was 34% at the 10% volume concentration in comparison to the base fluid. Moreover, a 50% enhancement of thermal conductivity was observed for the ethylene glycol (EG) based CuO nanofluid at 15% volume concentration. Similar results were obtained by several researchers for water-based Al_2O_3 nanofluids [6–8]. A few studies published the relationship between particle size and thermal conductivity. Lee et al. [2], Wang et al. [5], Xie et al. [7,9,10], and Das et al. [8,11,12] conducted thermal conductivity measurements of nanofluids using 20–60 nm spherical nanoparticles in water and found that the thermal conductivity of the nanofluid generally diminishes as the particle size becomes larger.

For the practical application of nanofluids, the accurate properties of nanofluids must be measured and analyzed, such as the effective thermal conductivity, the particle size and the dispersion stability. In particular, the dispersion stability should be evaluated by measuring the exact amount of suspended and settled nanoparticles in the base fluid over time. Several methods were used to evaluate the dispersion stability of nanofluids, which are listed in Table 1. These methods are able to determine the degree of dispersion between the initial state of the nanofluid preparation and afterwards. However, it is especially challenging to analyze both the absolute amount of nanoparticles in a nanofluid and the quantitative characteristics of dispersion stability. In addition, the nanoparticles agglomerate and settle with time, resulting in variations of the volume fraction and particle size distribution, upon which the nanofluid thermal conductivity strongly depend. Therefore, the temporal state of the particle size variation and suspended particle concentration must be evaluated, and then presented together with the thermal conductivity measurement.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.11.029

Nomenclature

DLS	dynamic light scattering
L	length (m)
$\dot{Q}$	heat transfer rate (W)
R	resistance (Ω)
R_O	resistance at 273.15 K (Ω)
SEM	scanning electron microscope
T	temperature (K)
TEM	transmission electron microscope
k	thermal conductivity (W/mK)
t	time (sec)

Greek symbols

α	temperature coefficient of resistivity (1/K)
ϕ	volume fraction of nanofluid
ρ	density (kg/m^3)

Subscripts

n	nanofluid
f	base fluid
p	particle
w	wire

In this study, a novel method is proposed for the quantitative analysis of the dispersion stability. A hydrometer is utilized to measure the particle volume fraction of each of the nanofluids studied. The particle size and distribution is determined by using the DLS method. From the analysis of the combined results, the dispersion stability of each of the nanofluids is evaluated. The effective thermal conductivity of each of the nanofluids is measured using the transient hotwire method and is observed to be strongly dependent on the variations of particle volume fraction and size distribution with time.

2. Theory and experimental setup

2.1. Nanofluid preparation and stability monitoring method

Five different nanofluids were generated using one-step and two-step methods. Water-based Ag nanofluids and EG-based ZnO nanofluids were produced in KIER (Korea Institute of Energy Research) using a one-step method. Water-based Al_2O_3 and SiO_2 nanofluids and EG-based Al_2O_3 nanofluids were prepared in the laboratory using nanopowder from Nanostructured & Amorphous Materials Inc. Five different nanofluids were chosen to observe the differences between the nanofluids prepared by the one-step and two-step methods. Furthermore, the chosen nanofluids are the most commonly used materials in nanofluids research [1–3,5,7,10–17]. The nanofluids were homogenized using a bar type sonicator for three hours to ensure the initial stability of nanofluids. The specific gravity or density of each nanofluid was measured using a hydrometer (GP-300S, MATSUHAKU) to estimate the volume fraction of the nanofluid using Eq. (1).

$$\phi = \frac{\rho_n - \rho_f}{\rho_p - \rho_f} \tag{1}$$

where ϕ is the volume concentration of the nanofluid, ρ_n is the density of the nanofluid, ρ_f is the density of the base fluid, and ρ_p is the particle density. When the hydrometer was utilized for the volume concentration measurement, the initial volume concentration of the water-based Ag nanofluid was 0.7% and that of the EG-based ZnO was 1.3%.

The nanofluid stability is determined by the aggregation and sedimentation of particles, which are induced by particle interactions. The sedimentation is monitored by measuring the real-time density of the nanofluid utilizing a hydrometer, which can be converted to the volume concentration by using Eq. (1). The aggregation of particles is monitored by measuring the variation of particle size and particle size distribution with time. The SEM or TEM are good methods to visualize nanoparticles in nanofluids; however, they are not sufficient to obtain statistical results because only from tens to hundreds particles are measured among a large number of particles. Therefore, the particle size was measured using the DLS (Dynamic Light Scattering) method to confirm the particle size over a larger sample size. When the particle size in suspension is under tens of micrometer, the particles undergo random thermal motion by Brownian motion, and the speed of the particle movement varies according to the Stokes–Einstein equation depending on the particle size. The smaller particles move faster, and the larger particles move more slowly. An incident laser beam to this particle laden suspension induces scattering of phase shifted laser light via the Doppler shift. The size and size distribution of the suspended nanoparticles were analyzed using this DLS method (ELS-Z, OTSUKA, Japan).

2.2. Nanofluid thermal conductivity measurement

Applying voltage to a hot wire causes a temperature rise of the sample fluid surrounding the hot wire that depends on the fluid

Table 1
Comparison of various methods for estimation of nanofluid stability.

Authors	Method	Materials	Remarks
Hwang et al. [13]	UV–vis. spectrophotometer	MWCNTs, Fullerene/oil	Nanofluid stability was estimated by using UV–vis. spectrophotometer. Absorption and particle concentration showed linear relation. From the relation, the relative stability of nanofluids was estimated.
Wang et al. [15]	Malvern ZS Nano S analyzer (DLS)	Alumina, Cu/water	Well-dispersed suspension was obtained with high surface charge density. The greater the zeta potential, the more stable the suspension.
Chen et al. [16]	Small Angle X-ray Scattering (SAXS)	Ludox	Analysis of X-ray scattering from particles in a liquid can be complicated by interference between the X-rays elastically scattered from individual particles. Using the SAXS to characterize particle size distribution in silica nanofluids.
Wensel et al. [21]	Visual inspection	Nanotube/water	The dispersion stability of nanofluids containing nanotube and metal oxide particles was determined by visual inspection
Chiesa and Simonsen. [22]	Transmission Electron Microscopy (TEM)	Alumina/oil	Nanofluid stabilities were estimated by TEM image. Nanofluids were stable if the nanoparticles seem to be well distributed