Int J Thermophys (2008) 29:1968–1973
DOI 10.1007/s10765-008-0529-3

Thermal Conductivity of AlN–Ethanol Nanofluids

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Published online: 7 November 2008

Abstract Aluminum nitride (AlN) particles of 20 nm diameter were dispersed into ethanol by a two-step process, first magnetic striation and then ultrasonic agitation. Castor oil was added as a dispersant to improve the stability of the AlN suspension. The thermal conductivities of AlN–ethanol nanofluids were measured by a hot-disk method from 0.5 vol% to 4.0 vol% at temperatures of 273.15 K and 297.15 K. Results show about 20 % increase in the thermal conductivity of ethanol with the addition of 4.0 vol% at 273.15 K, and a strong temperature dependence of the thermal conductivity.

Keywords AlN · Ethanol · Nanofluid · Thermal conductivity

1 Introduction

Thermal convection is one of the main heat transfer processes; its efficacy mostly depends on the thermophysical properties of conventional fluids. The low thermal conductivity of a conventional fluid is the primary limitation for heat transfer. Dispersing solid particles in fluids is an efficacious way of improving the thermal conductivity of fluids since the thermal conductivities of most solid materials are orders of magnitude larger than those of traditional heat transfer fluids. Unfortunately, suspended particles of micrometer or millimeter dimensions have some obvious disadvantages, such as

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abrasion and clogging in small passages, and poor stability; the solid particles may settle out of the suspensions and deposit on heating/cooling wall surfaces. Recently, there has been a growing interest in using nanoparticles as additives to improve the thermal conductivity of fluids, and these solid–liquid composite materials are called nanofluids, which consist of solid nanoparticles or nanofibers with sizes <100 nm suspended in a liquid [1,2]. The small size of nanoparticles can improve the stability of the suspensions, which usually have an ultrahigh thermal conductivity. Thermal conductivities of some nanoparticle suspensions, such as Cu, CuO, Al_2O_3, SiC, carbon nanotubes, etc., have been reported. Keblinski et al. [2] have given a detailed review on this field.

Aluminum nitride (AlN) is one of the typical ceramics that have special properties such as high thermal conductivity (8 to 10 times that of Al_2O_3), low dielectric coefficient (about 8.15), high electrical resistance, and low density. Because of these advantageous properties, it is used in various engineering applications and has attracted the intense interest of researchers. However, few results concerning AlN nanofluids have been reported. In this work, AlN particles with an average diameter of 20 nm were dispersed into ethanol to obtain the desired nanofluids, with castor oil as the selected dispersant. The thermal conductivities of AlN nanofluids were measured by the hot-disk method from 0.5 vol% to 4.0 vol% at temperatures of 273.15 K and 297.15 K. Experimental results were compared with calculated values by a theoretical model.

2 Measurements

2.1 Sample Preparation

AlN particles with an average diameter of 20 nm were used in the present experiment. The samples were produced by a plasma arc in the gas phase with 99.0 % purity, provided by Hefei Kiln Nanometer Technology Development Co., Ltd. AlN nanoparticle suspensions were prepared by first adding AlN nanoparticles to ethanol with castor oil as the dispersant to improve suspension stability, and then stirred with a high-speed magnetic stirrer. The resulting suspension was placed in an ultrasonic homogenizer for 10 min. There are three kinds of dispersants for AlN particle–ethanol suspensions: NH_4PAA, polyethylene imine (PEI), and castor oil [3,4]. In this work, castor oil, the most easily available, was used. The main component of castor oil is ricinoleic acid (CH_3–$(CH_2)_5$–CH(OH)CH_2CH=CH$(CH_2)_7$–COOH), which is a typical long-chain molecule. It can be adsorbed on the surface of AlN particles and prevent them from clustering through a strong steric effect. The prepared samples can remain stable for more than two weeks without settling. Figure 1 is a photograph of AlN nanofluids. Figure 2 is a TEM photograph of 1 vol% AlN nanofluid taken by JEM-2010 (JEOL, Ltd., Japan). In this photograph, the sample has been magnified 30,000 times and the figure shows that AlN nanoparticles were deagglomerated and homogenized.

2.2 Experimental Instrument and Procedures

The measuring instrument is the hot-disk thermal constant analyzer. The hot-disk method is an experimental technique developed from the concept of the transient

Fig. 1 Photograph of AlN–ethanol nanofluid

hot-strip (THS) technique, first introduced by Gustafsson [5]. The hot-disk analyzer system is based on the transient plane source (TPS) method [6], which is one of the most precise and convenient techniques for studying thermal transport properties. The system components are presented in Fig. 3.

The planar hot-disk sensor is covered with Kapton film, placed into a nanofluid sample, and then heated by an electrical current for a short period of time. The dissipated heat causes a temperature rise of both the sensor and the surrounding nanofluid. The average temperature rise of the sensor, ranging from 0.5 K to 2 K, is measured by recording the change of the electrical resistance. Resistivity changes with temperature, and the temperature coefficient of resistivity (TCR) of the sensor material is determined in advance. By comparing the recorded transient temperature rise with that of the theoretical solution of the thermal conductivity equation, the thermal transport properties are deduced, such as the thermal conductivity and the thermal diffusivity, and also the specific heat of the sample. The thermal conductivity of pure ethanol was measured at room temperature four times; the deviations from the data in [7] are within 1 %.

3 Results and Discussion

In this study, the thermal conductivities of AlN nanofluids were measured by the hot-disk method from 0.5 vol% to 4.0 vol% at temperatures of 273.15 K and 297.15 K.

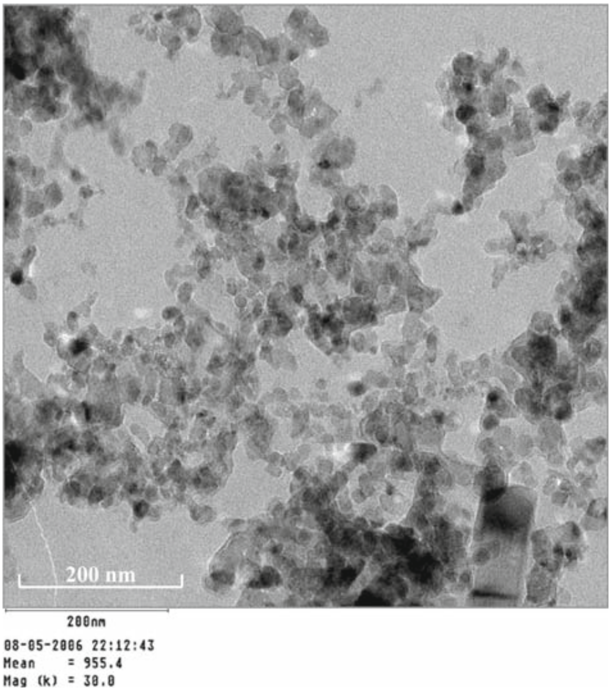

Fig. 2 TEM photograph of AlN–ethanol nanofluid with 1.0 vol% nanoparticles (×30,000)

The results show that the thermal conductivities of the suspensions containing a small amount of AlN nanoparticles are substantially higher than that of the base fluid. The thermal conductivity can be increased by about 20 % at a volume fraction of 4 % at 273.15 K as shown in Fig. 4. The measured data clearly indicate that the ratios of the thermal conductivities of AlN suspensions increase nonlinearly with the volume fraction. The curves of thermal conductivities at 273.15 K and 293.15 K cross at a volume fraction of about 2.75 %. The result is probably based on the relation between the temperature and Brownian motion and agglomeration of nanoparticles. At low volume fractions, nanoparticles have more intense Brownian motion at higher temperatures, which can significantly enhance the effective thermal conductivity. But at high volume fractions, nanoparticles have high potential to be agglomerated at high temperatures. Therefore, the effective thermal conductivity of AlN nanofluids with a high volume fraction is potentially lower than that of AlN nanofluids with a low volume fraction at high temperatures.

Various theories have been developed to determine the thermal conductivity of solid particle suspensions. In the present investigation, the Hamilton and Crosser model is employed [8], which has the form

$$\frac{k_e}{k_0} = \frac{k_p + (n-1)\,k_0 - (n-1)\left(k_0 - k_p\right) f}{k_p + (n-1)\,k_0 + \left(k_0 - k_p\right) f} \tag{1}$$

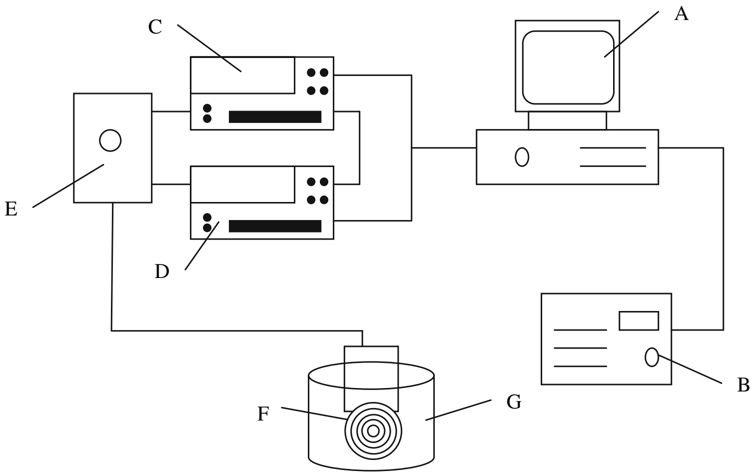

Fig. 3 Hot-disk thermal constant analyzer system. (A) Computer. (B) Computation device. (C) Keithley 2000. (D) Keithley 2400. (E) Hot-disk bridge. (F) Sensor. (G) Samples

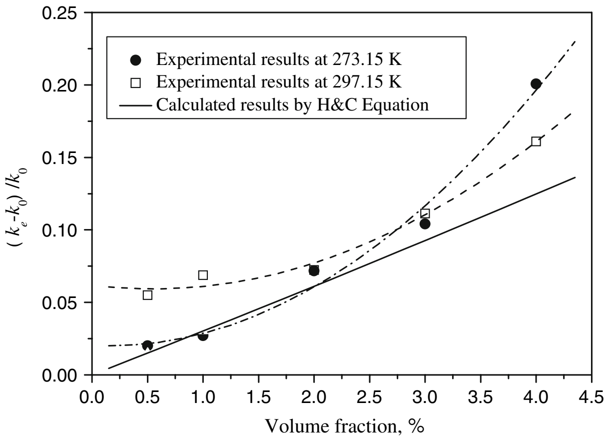

Fig. 4 Measured and calculated thermal conductivities of AlN–ethanol nanofluids

where k_{p} is the thermal conductivity of particles, k_0 is the thermal conductivity of the base liquid, f is the volume fraction of nanoparticles, and n is the shape factor: for spheres, $n = 3$, and for cylinders, $n = 6$. An AlN nanoparticle is a hexagonal crystal, which is quite close to a sphere. In Fig. 4 the solid line represents the calculated thermal conductivity enhancement ratios of an AlN nanoparticle suspension system with $n = 3$.

The theoretical Hamilton and Crosser model for predicting the thermal conductivity is only dependent on the thermal conductivity of the solid particles and the base liquid and the volume fraction of the solid particles, and not on the particle size and the interfacial properties [9]. Therefore, comparisons with the experimental data always show that the predictions are lower than the experimental data.

4 Conclusions

AlN particles of 20 nm diameter were dispersed into ethanol by a two-step process, first magnetic striation and then ultrasonic agitation. Castor oil is added as a dispersant to improve the stability of the AlN suspension. The thermal conductivity of an AlN nanofluid is measured by the hot-disk method from 0.5 vol% to 4.0 vol% at temperatures of 273.15 K and 297.15 K. Results show a 20 % increase in the thermal conductivity of ethanol with the addition of 4.0 vol% at 273.15 K, and a strong temperature dependence of the thermal conductivity.

References

1. S.U.S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, in *Developments and Applications of Non-Newtonian Flows*, ed. by D.A. Singer, H.P. Wang (Am. Soc. Mech. Eng., New York, 1995), pp. 99–106
2. P. Keblinski, J.A. Eastman, D.G. Cahill, Mater. Today **8**, 36 (2005)
3. Z. Wang, Z. Ni, D. Qiu, G. Tao, P. Yang, J. Anal. At. Spectrom. **20**, 315 (2005)
4. H. Huang, H. Zhou, Y. Wang, J. Inorg. Mater. **17**, 380 (2002) [in Chinese]
5. S.E. Gustafsson, Rev. Sci. Instrum **62**, 797 (1991)
6. T. Log, S.E. Gustafsson, Fire Mater. **19**, 43 (1995)
7. Y.S. Touloukian, P.E. Liley, S.C. Saxena, *Thermal Conductivity: Nonmetallic Liquids and Gases, Thermophysical Properties of Matter*, vol. 3 (IFI/Plenum, New York, 1970)
8. R.L. Hamilton, O.K. Crosser, Ind. Eng. Chem. Fundam. **1**, 187 (1962)
9. Q. Xue, W.-M. Xu, Mater. Chem. Phys. **90**, 298 (2005)