The Development of a Microfabricated Transient Planar Source (TPS) Sensor for Measuring Thermal Conductivity of Nanofluids

Apichai Jomphoak[*, 1, 2,] Thitima Maturos[1], Tawee Pogfay[1],
Chanpen Karuwan[1], Adisorn Tuantranont[1], and Thawatchai Onjun[3]

[1]National Electronics and Computer Technology Center (NECTEC), Thailand Science Park, Pathum Thani 12120, Thailand

[2]School Of Communications Instrumentations and Control Sirindhorn Internationel Institute of Technology, Thammasat University, Klong Luang Pathum Thani 12120, Thailand

[3] School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Klong Luang, Pathum Thani, 12121, Thailand

E-mail: apichai.jomphoak@nectec.or.th

Abstract

A re-design of the sensor for measuring thermal conductivity of nanofluids is developed. The Transient Planar Source (TPS) method is used to measure the thermal conductivity of a nanofluid. This TPS sensing element consists of a heat source and a temperature sensor, where the temperature coefficient of resistance is derived from a calibration of the sensor, in a measurement of the resistance across the leads of the sensor. The TPS system (Hot Disk) consists of a 10-mm-diameter sensor head fixed into a nanofluid measurement chamber, This sensor is used to measure the thermal conductivity of Cu-H_2O nanofluids with the effect of pH surfactant included. These nanofluids were prepared by a two-step method, which results in an average 100-nm particle size distribution. To improve the dispersion behavior, a surfactant at pH 9.2 is also used. The method shows good utility for measuring a thermal conductivity at a wide range of temperatures.

Keywords: Nanofluids, TPS, Thermal conductivity, Sensor

1. Introduction

Due to the greatly increasing thermal load in microelectronics and higher-powered automobiles, the needs for high performance heating or cooling fluids have consistently increased [1]. As a result, the thermal conductivity of these fluids plays a vital role in the development of energy-efficient heat transfer equipment. However, conventional heat transfer fluids have poor heat transfer properties compared to most solids; large potential mechanisms for thermal conductivity enhancement such as Brownian motion, liquid layering and nanoparticle clustering, the suspension stability are common factors in the current technological limitations, as surface chemical treatment changes the suspension stability through surface charge states and resultant surface potential [2-8]. Therefore, in the present study we chang pH of the suspension systematically to control surface potential. The effects of the pH value on the aqueous suspension, sodium dodecylbenzenesulfonate concentration, and the weight fraction of the dispersed Cu particles on the enhanced thermal conductivity ratio have effectively enhance a thermal conductivity of such reported fluids [9]. The promising prospect for nanofluids triggered many researchers to find the best combination of particles and solvents and to elucidate the governing mechanisms as well. This is expected to provide guidance to design nanofluids with excellent performance.

2. Experiment

2.1 Sensor Fabrication

The microfabrication technique can be used as a novel solution to eliminete Eliminating the electroplating proass from the former technique which results in the remaining processes to lae only (the lithography and sputtering processes). The difference of this technique over the hot wire technique [14] is that the positive patterns in Fig. 1 are first printed on transparency film, which acts as a mask. The rest of the procedures in lithography are unchanged, except the dry film or negative resist will still be laminated on a glass substrate, but under the same temperature at 80oC, and then exposed to UV-light under the patterned transparency film for 3.2 seconds (which is slightly longer).

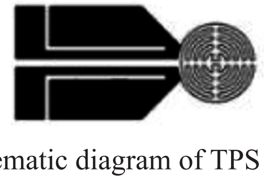

Fig. 1. Schematic diagram of TPS sensor.

2.1.1 Designing the mask pattern of the sensor systems

In order to design the desired sensor pattern, the resistivity of the device must be taken into consideration, which depends on the thickness of the sensor. The appropriate resistivity of the device should be in the range of 100-200 Ω. The simulation design and calculation of the resistivity, where ϱ is the electrical resistivity of gold and has a value of 0.022x10-3 Ω•mm^2/mm at 20 °C. The longitudinal length of the hot disk, l, is 0.4555316 mm, and the minimum range of cross sectional area (A) is 0.000075 - 0.000150 mm^2. As cross sectional area of sensor increases, its resistivity decreases, reflected by sputtering time.

COMSOL Multiphysics® is a tool to design models for Micro-electro-mechanical system (MEMS) and microfluidics devices. The process of simulation begins with creating a 2-D layout and building 3-D model geometries, generating a mesh for the finite elements, creating variables and expressions used within a model, solving the mesh by using its solvers, and finally analyzing results from its solvers by postprocessing and visualization tools. The analyzed results can be illustrated by advanced graphics, data display and export functions, and a report generator. Fig. 2 shows the process of simulation by using COMSOL Multiphysics

An important part of the process is to create a geometry of the sensor. A common way of creating 3D geometries is to model a 2D cross section and create the 3D objects using extrude and revolve operations or embedding 2D geometries into the 3D geometry model, as shown in Fig. 2.

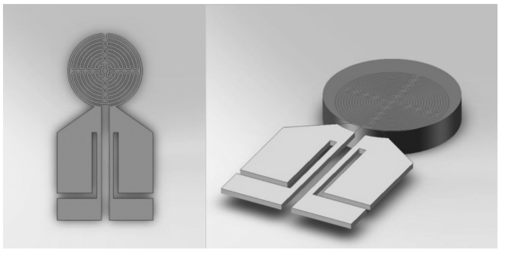

Fig. 2. A 2D layout of transient planar source (TPS) sensor.

In this work, the TPS sensor system consists of a 10-mm-diameter sensor head with 5-μm thickness fixed into a nanofluid measurement chamber. 2D cross sections are created in local 2D coordinate systems, called work planes, which can be positioned anywhere in 3D space. An advantage with this approach is that the snap-to-grid and snap-to-vertex features can be used to connect different geometric parts together.

2.1.2 Lithography Process

The gold patterns for bond pads are printed on transparency film, which acts as a mask for the lithography process. PCB dry film, negative resist, is laminated on stainless plate under temperature 80°C, and then exposed to UV-light under the patterned transparency film for 3 seconds (Mask aligner machine has wavelength 405 nm and the power of Hg-lamp is 308 Watts). After exposure, the designed patterns are transferred onto negative-resist and the exposed areas become harder and the unexposed areas remain the same.

2.1.3 Sputtering Process

A glass slide with Ni-mask was thermally evaporated with Cr/Au metal. Firstly, a Cr layer was growm to about 30 nm for good adhesion between 200 nm of Au layer and glass slide (Initial Pressure, Evaporation rate for thermal evaporation).

2.2 Nanofluids Preparation

Ultrasonication was used for the preparation of mixed aqueous nano-suspensions, and widely used technique for dispersing the highly entangled or aggregated nanoparticle samples. However, a longer time of high-energy sonication can introduce defects. In the study, copper nanoparticle (0.05 g) and a water solution (99.95 g) with 9.2 pH buffer were directly mixed in a 100 Wat beaker. The suspension was transferred into an ultrasonic vibrator and sonicated for 45 min at a frequency of 40kHz and an output power of 100W at 25-30°C. For the comparison, the suspension without buffer was sonicated for 45 min in the same way. Fig. 3 illustrates the particle size distributions of Cu-H_2O and Alumina nanosuspensions. This shows that there are obvious variations in the particle size characteristics between the two nanofluids.

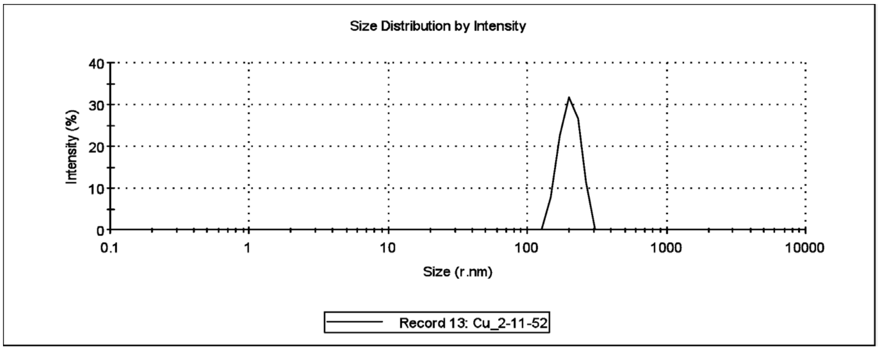

Fig. 3 Particle size distributions of Cu-H_2O.

2.3 Measurement of Thermal Conductivity of Nanofluids

2.3.1 Transient Plane Source (TPS) Theory

Thermal conductivity of nanofluids is measured by means of the TPS method. In this method, the TPS element behaves both as temperature sensor and heat source. This novel method offers some advantages such as fast and easy experiments, wide range of thermal conductivities (from 0.02 to 200 W/mK), no sample preparation and, flexible sample size. The TPS element consists of an electrical conducting pattern of thin gold foil (4 um) in the form of a spiral, which resembles a hot disk (see Fig. 4) dipped into suspensions. A constant electric power (DC-voltage power supply) is supplied to the sensor and the increase in temperature T(τ) is calculated from the variation in the sensor resistance with time R(t) by using the equation:

$$\Delta T(\tau) = \frac{1}{\alpha}\left(\frac{R(t)}{R_0} - 1\right) \qquad (1)$$

where R0 is the hot-disk resistance in the beginning of the recording (initial resistance), α is the temperature coefficient of resistance of the nickel foil, and T(τ) is the temperature increase of the sensor expressed in terms of the variable τ, defined as:

$$\tau = \sqrt{\frac{t}{\theta}},\ \theta = \frac{a^2}{\kappa} \qquad (2)$$

where t is the measurement time, θ is the characteristic time, which depends both of parameters of the sensor (a is the sensor radius) and the sample (k is the thermal diffusivity of the sample). Fig. 5 shows the sensor temperature variation in a typical transient heating. Assuming the conductive pattern to be in the Y-Z plane of a coordinate system, the temperature rise at a point (y, z) at time t is due to an output of power per unit area.

2.3.2 Measurement process of the thermal conductivity of nanofluids

Different concentration nano-suspensions were prepared, which were stirred thoroughly and ultrasonicated for half of an hour. A device was successively dipped into the different nano-suspensions. The diameter of the sensing spiral was about 10.0 mm with a thickness of 4 um. The measurement was run at V = 0.02 Volt, T=25°C with switch time at t = 5 sec. Each experiment was repeated at least ten times to calculate the mean value of the experimental data. The pH value of the system was adjusted with HCl and NaOH solution by pH Meter (827 pH Lab, Metrohm, Switzerland). Before systematic experiments were performed on Cu-H2O nanofluids, the experimental system was tested with deionized water as the working fluid. The results with the deionized water will also serve as the basis for comparison with the results of nanofluids. The uncertainty of our measurements is calculated to be less than 1.00 %.

3. Results

3.1 Influence of pH on Thermal Conductivity of Copper Nano-Suspensions

Fig. 5 shows the change of Cu-H_2O s uspensions as a function of pH. According to the potential values of copper powders, pH 8.5-9.5 can be selected as an operating pH for the suspensions. Because, at the pH, the values of potential for Cu-H_2O suspensions is higher, so there are more surface charges around the particles. Fig. 5 shows the change of thermal conductivity ratio for Cu-H_2O

suspensions as a function of pH. It can be seen that the thermal conductivity ratio increases as pH increases from 3 to 8.5-9.5. When the nanoparticles are dispersed into water, the overall behavior of the particle-water interaction depends on the properties of the particle surface. The repulsive forces among copper particles is zero and nanoparticles will coagulate together under this pH value. The hydration forces among particles increase with the increasing difference of the pH value of a suspension, which results in the enhanced mobility of nanoparticles in the suspension. The microscopic motions of the particles cause microconvection that enhances the heat transport process. So we attempt to link the concept of surface charges to the change in thermal conductivity ratio of nanofluids. The point to mention is that the charged surface sites seemingly provide much more effective passages through which heat or phonons are flowing more efficiently. The surface charge states are mainly responsible for the increase of thermal conductivity in the present condition as show by the surface model for the measurement data of hydrodynamic size, zeta potential, and thermal conductivity. Therefore, it looks reasonable to infer that optimizing pH or higher surface charging conditions facilitate transport through increases of effective sites and transport efficiency. In this way, we can infer that there are more surface charges at pH 8.5-9.5, at which the dispersion behavior is better and the thermal conductivity is higher.

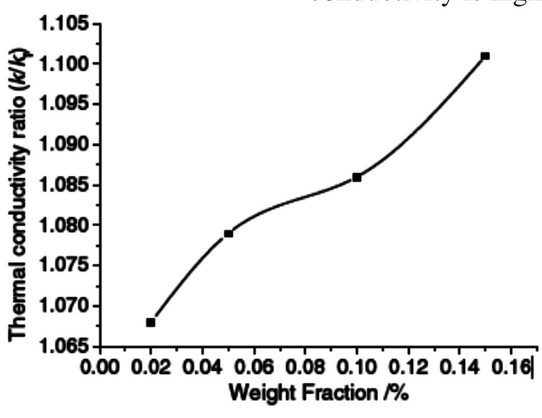

Fig. 4. Effect of mass fraction on thermal conductivity of Cu-H2O suspensions.

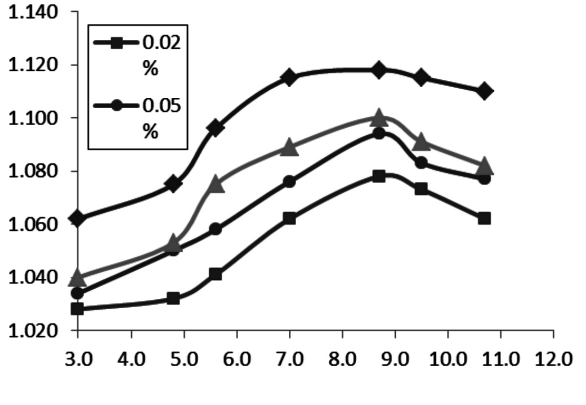

Fig. 5. Effect of pH on thermal conductivity of Cu-H2O suspensions.

3.2 Influence of the concentration on thermal conductivity of nano-suspensions

Fig. 7 presents the thermal conductivity ratio of the Cu-H_2O suspensions and the base fluid with respect to the concentration at pH 8.5–9.5. The weight fraction of the Cu-H_2O suspensions is 0.1 wt%. For the base fluid, the thermal conductivity ratio starts to decrease after a certain value of the surfactant concentration. In the present experiments, the highest thermal conductivity appears at 0.02 wt% water solution, which means when an ounce of surfactant is added, the thermal conductivity at 0.02 wt% water solution is higher than that of pure water. In the 0.1 wt% Cu-H_2O suspensions, the trend of the variation of the thermal conductivity is similar to those in the base fluid with surfactant only. However, the thermal conductivity ratio decreases slowly as concentration increases from 0.02 wt% to 0.10 wt%, and then decreases very quickly with an increase in the concentration. For the Cu-H_2O suspensions and the base fluid, when more pH is added into the systems, the thermal conductivity ratios decrease very quickly. Owing to this trend, the addition of more surfactant seems non-effective in the Cu-H_2O suspensions. This is because the heat transfer area becomes narrower due to the amount of the surfactants on the particle surface. Taking into account the combined effect of dispersion behavior and thermal conductivity, the 0.10 wt% can be selected as an optimizing concentration for the 0.1% copper nano-suspensions. Therefore, it can be concluded that the application of nanofluid with optimizing chemical surfactant is a better way among the considered enhancement techniques in the viewpoint of the effectiveness of dispersion behavior and thermal conductivity.

3.3 Influence of the weight fraction of nanoparticle on thermal conductivity

Fig. 8 shows the enhanced thermal conductivity ratio of Cu-H_2O suspensions with the optimizing concentration as a function of the weight fraction of nanoparticles. The range of pH 8.5-9.5 can be selected as an operating pH for different weight fraction suspensions. The results show that an ounce of nanoparticle suspensions have noticeably higher thermal conductivities than the base fluid without nanoparticles. The thermal conductivity of Cu-H_2O nanofluid is enhanced approximately nonlinearly with the weight fraction of the copper nanoparticle. Then it implies that Cu-H_2O suspensions can enhance the heat transfer performance. The maximum thermal conductivity increases up to 10.7% at 0.10 wt% suspension.

4. Discussion

Recent measurements showed that less than 1 vol. % copper nanoparticles in ethylene glycol improved the effective thermal conductivity 40%. In the low-volume-fraction range tested, the thermal conductivity ratios increased almost linearly with volume fraction, but with different rates of increase for each system. The experimental data also indicate that the thermal conductivitiesof nanofluids depended on the thermal conductivities of both the base fluids and particles. A new technique for measuring thermal conductivity, the Transient Planar Source (TPS) method, was used to investigate the thermal conductivity of automotive coolant and their equivalent nanofluid, as a function of temperature. The results of this study indicated that the TPS method allows for rapid and repeatable measurement of thermal conductivity with an error of between 2-4%.

Increased thermal conductivity would result in higher heat transfer than that of the based fluid without dispersed nanoparticles. Measurements of the heat transfer coefficients of nanofluids have shown that the heat transfer capability of water increases by 15% with a dispersion of less than 1 vol. % copper oxide nanoparticles. About 80% increases in heat transfer with the dispersion of less than 3 vol. % of alumina nanoparticles were found recently in this research. It should be noted that the observed heat transfer rates of nanofluids were much higher than those predicted by conventional heat transfer correlations, even when thermo-physical properties such as thermal conductivity, density, specific heat, and viscosity were considered. It appeared that the effect of particle size and number are important for heat transfer in nanofluids.

5. Conclusions

This research aims to develop a novel and improved design of sensor device for measuring thermal conductivity of Cu-H2O and Al2O3-H2O nanofluid under different pH values and different concentrations. The thermal conductivity of nanofluids are measured by using the transient plane source method. The sensor device is optimized and re-designed by using COMSOL Multiphysics, and then fabricated by microfabrication using lift-off technique. the key conclusions can be summarized as follows:

1. Cu-H2O nanofluids by a two-step method were prepared. The particle size distribution shows better dispersion behavior in the suspension with the addition of surfactant.

2. The pH of the nanofluid strongly affects the thermal conductivity of the suspension. As the pH of the nanofluid increases, the surface charge increases, and the colloidal particles get more stable and eventually alter the thermal conductivity of the fluid. There are more surface charges at pH 8.5-9.5, at which the thermal conductivity is higher.

3. The use of Cu nanoparticles as the dispersed phase in water can significantly enhance the thermal conductivity, and the enhancement increases with particle concentration under the conditions of this work. Maximum thermal conductivityenhancements of up to 10.7% are observed at the 0.10 wt% suspension.

4. The thermal conductivity can be improved by adding optimizing surfactant. However, the combined treatment with both the pH change and chemical surfactant is recommended to improve the thermal conductivity for practical applications of nanofluids.

6. References

[1] W. Yu, U.S. Choi, The role of interfacial layers in the enhanced thermal conduc tivity of nanofluids: A renovated Ham ilton–Crosser model, J. Nanopart. Res. 6 (2004) 355–361.

[2] P. Keblinski, J.A. Eastman, D.G. Cahill, Nanofluids for thermal transport, Materials Today 8 (6) (2005) 36–44.

[3] H. Akoh, Y. Tsukasaki, S. Yatsuya, A. Tasaki, Magnetic properties of ferromagnetic ultrafine particles prepared by vacuum evaporation on running oil substrate, Journal of Crystal Growth 45 (1978) 495–500.

[4] M. Wagener, B.S. Murty, B. Gunther, Preparation of metal nanosuspensions by high-pressure DC-sputtering on running liquids, in: S. Komarnenl, J.C.

Parker, H.J. Wollenberger (Eds.), Nanocrystalline and Nanocomposite Materials II, Vol. 457, Materials Re search Society, Pittsburgh, PA, 1997, pp. 149-154.

[5] J.A. Eastman, U.S. Choi, S. Li, L.J. Thompson, S. Lee, Enhanced thermal conductivity through the development of nanofluids, Materials Research Society Symposium - Proceedings, Vol. 457, Materials Research Society, Pittsburgh, PA, USA, Boston, MA, USA, 1997, pp. 3-11.

[6] H. Zhu, Y. Lin, Y. Yin, A novel one-step chemical method for preparation of copper nanofluids, Journal of Colloid and Interface Science 227 (2004) 100-103.

[7] C.-H. Lo, T.-T. Tsung, L.-C. Chen, Shape-controlled synthesis of Cu based nanofluid using submerged arc nanoparticle synthesis system (SANSS), Journal of Crystal Growth 277 (1-4) (2005) 636-642.

[8] C.-H. Lo, T.-T. Tsung, L.-C. Chen, Ni nano-magnetic fluid prepared by submerged arc nano synthesis system (sanss), JSME International Journal, Series B: Fluids and Thermal Engineering 48 (4) (2006) 750–755.

[9] S. Lee, S.U.S. Choi, S. Li, J.A. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, Journal of Heat Transfer 121 (1999) 280-289.

[10] X. Wang, X. Xu, S.U.S. Choi, Thermal conductivity of nanoparticle-fluid mixture, Journal of Thermophysics and Heat Transfer 13 (4) (1999) 474-480.

[11] S.M.S. Murshed, K.C. Leong, C. Yang, Enhanced thermal conductivity of TiO2-water based nanofluids, Inter national Journal of Thermal Sciences 44 (4) (2005) 367–373.

[12] Y. Xuan, Q. Li, Heat transfer enhance ment of nanofluids, International Journal of Heat and Fluid Transfer 21 (2000) 58–64.

[13] Y.J. Hwang, Y.C. Ahn, H.S. Shin, C.G. Lee, G.T. Kim, H.S. Park, J.K. Lee, Investigation on characteristics of thermal conductivity enhancement of nanofluids, Current Applied Physics, in press.

[14] J. Kestin, W.A. Wakeham, A contribu tion to the theory of the transient hot-wire technique for thermal conductivity measurements, Physica A 92 (1978) 102–116.

[15] S.K. Das, N. Putta, P. Thiesen, W. Roetzel, Temperature dependence of thermal conductivity enhancement for nano fluids, ASME Trans. J. Heat Transfer 125 (2003) 567–574.

[16] Y. Nagasaka, A. Nagashima, Absolute measurement of the thermal conductivity of electrically conducting liquids by the transient hot-wire method, Journal of Physics E: Scientific Instruments 14 (1981) 1435–1440.