MEASUREMENT OF THERMAL CONDUCTIVITY OF COPPER NANOFLUID USING TRANSIENT HOT WIRE METHOD

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Abstract
The thermal conductivity measurement of electrically conducting copper nanofluid is addressed. The measurement principle is based on the transient hot wire method. A platinum wire coated with a thin electrical insulation layer is used as a heating element as well as a temperature sensor. The microcontroller based data acquisition system is provided for data sampling and processing of temperature of the sample with high sampling rate. The copper nanofluid is synthesized by reduction of copper sulfate with sodium borohydride in water without inert gas protection. It is found that the size of copper nanoparticle is 48nm from XRD analysis. The conductivity of nanofluid is measured after calibrating the device with distilled water and ethylene glycol. The enhancement of thermal conductivity is found to be 50.4% over the distilled water for the 1.0 vol. % copper nanofluids.

Keywords: nano-fluid, copper nano particles, thermal conductivity, transient hot wire method
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1. Introduction

The measurement of thermal conductivity of fluids is very important in evaluating the thermal transfer efficiency in thermal equipment and in cooling systems.In order to measure the thermal conductivity, a family of techniques named contact transient is becoming very attractive and popular for general use in the last years. The Transient Hot Wire (THW) has been widely accepted as the most accurate technique over a wide range of fluids. The most advantageous feature of the method applied to fluids is its capability of experimentally eliminating convective error and data obtained with this method is generally more reliable than those using the steady state method[1]. However, it is not possible to measure the thermal conductivity of conducting fluids using those methods where a bare thin metallic wire is used as an electrical heating element and a resistance thermometer. Although the principle of the method is apparently simple, its experimental implementation requires suitable temperature sensing, automatic control, data acquisition, and data analysis systems to be used. Because of the relatively short experimental times and large amounts of parametric data involved in the measurement process, computer control of the measurement is essential [2].

This paper addresses the design of the thermal conductivity measurement apparatus for nanofluids and the preparation of copper nanoparticles. Copper nanoparticles is synthesized to enhance the thermal conductivity of the liquid and to test the developed thermal conductivity apparatus. Using chemical reduction method, copper nanoparticles were prepared in a copper sulphate solution using $NaBH_4$ as reducing agent. Temperature and concentration ratio of reducing agent to precursor take effect on the synthetic progress and size of the copper nanoparticles. The particle size is analyzed by XRD.

Then the copper nanofluid is prepared by suspending very small volume concentrations of nanoparticles in deionized water or ethylene glycol.The measurement of thermal conductivity and data acquisition are accomplished by using the USB–2408 data acquisition device. The data logging and processing are carried out on the PC and the application program is designed by LabVIEW. The system acquires measured data with high speed and accuracy. In addition, the system allows for easy modification and enhancement of test parameters and measurement conditions by modification of the circuitry biasing and software programming.

2. Transient Hot-wire Model

For fluid thermal conductivity measurements, the THW technique is known to be a fast and accurate. The principle of the THW method is based on ideal, constant heat generation source, an infinitely long and thin continuous line, dissipating the heat into an infinite test medium. In practice, the ideal case is approximated with a finite long wire embedded in a finite medium. While the wire is electrically heated, the change in resistance of the wire, thus its temperature is measured as function of time using a Wheatstone bridge circuitry and a computerized data acquisition system. Finally, the thermal conductivity value is determined from the heating power and the slope of temperature change in logarithmic time[2].

The mathematical model for the THW method is based on an ideal, infinitely long and thin continuous line source dissipating heat, of heat flux q per unit length, applied at time t = 0, in an infinite and incompressible medium. It is also assumed that the line heat- source has uniform instant temperature everywhere, but transient in time (virtually achieved with small diameter and long wire with large thermal conductivity and/or small heat capacity). The governing equation (1) is derived from

the Fourier's equationfor one-dimensional transient heat conduction in cylindrical coordinates.

$$\frac{1}{\alpha_f}\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \qquad (1)$$

where , $T = T_0 + \Delta T$ is the temperature of the medium at any time t and arbitrary radial distance r, T_0 is the initial temperature of the source and medium, α_f thermal diffusivity and ΔT is the temperature difference between the medium and initial temperature. Using some boundary conditions and approximations for equation (1), the temperature rise at the radial distance r from the heat source is given by

$$\Delta T = T(r,t) - T_o = \frac{q}{4\pi\kappa_f}\left\{-\gamma + \ln\left(\frac{4\alpha_f t}{r^2}\right)\right\} \qquad (2)$$

where , $\gamma = 0.5772$ is the Euler's constant.

For constant fluid medium properties and a fixed and arbitrary radius *r*, after differentiation of equation (2), the radius is eliminated from the equation and the following relation is obtained [1],[2].

$$\kappa_f = \frac{q}{4\pi}\cdot\frac{1}{d(\Delta T)/d\ln(t)} \qquad (3)$$

Therefore, if temperature of the medium is measured as function of time at any fixed radial position, including the contact with the line source, the thermal conductivity of the test medium, κ_f, is proportional to the source heat flux and inversely proportional to the temperature (or temperature difference) gradient with regard to the natural logarithm of time in equation (3).

The advantage of the THW method is its simplicity and consequently low cost of construction. Furthermore, the wire itself acts as both the heating source and temperature sensor for measurement. Another advantage is that convection heat transfer effects can be minimized and identified when present as deviation of the linearity in the plot of **ΔT** as a function of ***ln (t)***.

In most THW method,a bare metal wire centered in a fluid medium is generally used for thermal conductivity measurement. For electrically conductive liquids, application of bare wire could lead to ambiguous results in the measurements. Using a bare metal wire the current will flow through the liquid and distortion of output voltage signal due to influence of the conducting liquid cell. These problems will be overcome, if the bare metal wire is coated using electrically insulating material. For a coated metal wire, the temperature rise ΔT of the HW is given as[2],

$$\Delta T = \frac{q}{4\pi\kappa_f}\left[\ln t + A_o + \frac{1}{t}(B_o \ln t + C_o)\right] \qquad (4)$$

The coefficients A_o, B_o and C_o are defined as

$$A_0 = \ln\left(\frac{4\alpha_f}{r_0^2\gamma}\right) + \frac{2\kappa_f}{\kappa_i}\ln\frac{r_0}{r_w} + \frac{\kappa_f}{2\kappa_w} + \ldots\ldots \qquad (4)$$

$$B_o = \frac{1}{2\kappa_f}\left\{r_w^2\left(\frac{\kappa_i}{\alpha_i} - \frac{\kappa_w}{\alpha_w}\right) + r_0^2\left(\frac{\kappa_f}{\alpha_f} - \frac{\kappa_i}{\alpha_i}\right)\right\}$$

$$C_0 = \frac{r_w^2}{8}\left\{\left(\frac{\kappa_f - \kappa_i}{\kappa_w}\right)\left(\frac{1}{\alpha_w} - \frac{1}{\alpha_i}\right) + \frac{4}{\alpha_i} - \frac{2}{\alpha_w}\right\} + \frac{r_0^2}{2}\left(\frac{1}{\alpha_f} - \frac{1}{\alpha_i}\right) + \frac{r_w^2}{\kappa_i}\left(\frac{\kappa_i}{\alpha_i} - \frac{\kappa_w}{\alpha_w}\right)ln\left(\frac{r_0}{r_w}\right) + \frac{1}{2\kappa_f}\left\{r_w^2\left(\frac{\kappa_i}{\alpha_i} - \frac{\kappa_w}{\alpha_w}\right) + r_0^2\left(\frac{\kappa_f}{\alpha_f} - \frac{\kappa_i}{\alpha_i}\right)\right\}\ln\frac{4\alpha_f}{r_0\gamma}$$

wherer_w is the radius of the wire, and r_0 is the sum of the radius of the wire r_w and the insulation thickness δ_i. Subscript w, I and f represent wire, insulation coating and liquid, respectively[2].

The term (1/t) (B_o ln (t) + C_o) is due to the presence of the insulation layer on the wire and it is negligibly small compared to the (ln(t) + A_o) term if the insulation coating thickness is comparable to the wire radius. The constant $A_o$shifts (i.e., offsets) the plot of ΔT against ln(t), without changing the slope. Therefore, the thermal conductivity, κ_f, is again accurately determined using equation (3).

3. Design of THW Apparatus

TheTHW cell is designedin order to reduce the test sample volume and to provide a controlled tension in the HW during heating and thermal dilatation. The design also provides a flexible method to easily replace the sample and disassemble the cell to clean the parts. There are some of the important designs factors considered in this work which are flexibility in handling and cleaning, suspension and centering of the platinum HW, connection of the leads to the HW, electrical wire routing, temperature measurement of the sample and electrical and signal wiring connections.

Platinum has been selected as superior HW material. It has higher thermal conductivity compared to the nichrome and tantalum also used as hot-wires. Teflon has been selected as insulating material for the HW as it is highly resistant to chemical reactions, corrosion and stress-cracking at high temperatures. A 50.8μm diameter platinum wire with a Teflon insulation coating of 25.4μm thickness, manufactured by A-M Systems, Inc ., has been used as the hot-wire. Care has been taken to avoid any disruption of the coating during HW mounting.

A cross sectional view of the designed HW thermal conductivity apparatus with major mechanical components is shown in Fig.1. The outer shell acts as the sample test fluid reservoir. The cell cap, designed to slide-fit into the outer shell, is hollow inside. The inner semi-circular HW holder with an alignment ring is soldered at the lower end at an offset. A HW guiding block, sliding tube, tension spring, and spring rod are all aligned at an offset inside the cap. The Teflon-coated platinum wire is indirectly connected to the tension spring via copper wires and a sliding rod which are aligned with the spring mechanism. A locking nut,

fastened to the spring rod, is mounted on the top of the cap. Two symmetric rectangular cuts in the cap provide an opening for routing of electrical and thermocouple wires. A connector and a wire holder, made of Teflon, are mounted on the top and middle section of the cell cap. Two thermocouples, mounted on the outer radius of inner semi-circular HW holder, along the length of the sample test section, monitor uniformity of the test fluid temperature. The cell parameters are given in table 1.

Table 1 Design parameters for THW cell

Length of platinum wire	0.152 *m*
Diameter of platinum wire (Teflon coating)	50.8 µm
Thickness of Teflon coating	0.0254mm
Internal diameter of sample holder	2.6c m
Volume of liquid sample	50 ml

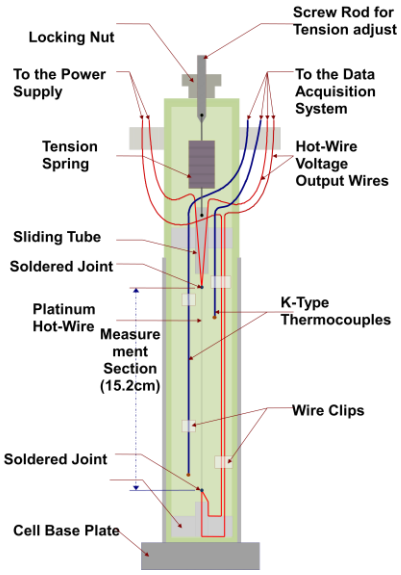

Figure 1.Cross- sectional view of THW thermal conductivity apparatus

4. Electronics of Thermal Conductivity Measurement

The electronic circuit and data processing system is illustrated in Fig.2. The resistance change of HW is measure with a Wheatstone bridge circuit and the wire is connected to one arm of the bridge. Initially, to balance the bridge the variable resistor at the one of the arms is adjusted until the voltage output of 10-20 µV is achieved. Low input voltage of 1V is used to perform the bridge balancing to minimize heating of the platinum wire. After the bridge circuit is balanced, a constant, input voltage V_{in}(at start-time t = 0) is applied to heat the wire, thus resulting in unbalancing of the bridge due to the HW's temperature and thus resistance change. The bridge input V_{in} and output V_{out}voltages are measured using a computerized data acquisition system. Four different signals namely: bridge voltage output, hot-wire-voltage drop (i.e., voltage drop across platinum wire) and two signals from the thermocouples mounted across the length of the HW cell at the top and bottom sections are measured using National Instruments data acquisition hardware. A computer program for acquiring and post-processing the measured data is developed using LabVIEW application software.

All measurement parameters are controlled using the labVIEW graphical user interface. The input voltage range is configured to be 0-5V. The voltage output channel can be configured at a maximum sampling rate of 30Hz, with nominal operation range of 0-200 mV. The bridge voltage output and time are measured simultaneously and stored as the data file in personal computer memory. Then the data is processed to calculate the resistance change, temperature change, heat input and thermal conductivity of the test fluid. Fig.3shows the photograph of the experimental setup.

5. Preparation of Nanofluid

Copper nanoparticles were synthesized through the chemical reduction of copper sulfate with sodium borohydride in water without inert gas protection[3]. In the synthesis route, ascorbic acid (natural vitamin C) is employed as a protective agent to prevent the Cu nanoparticles from oxidation during the synthesis

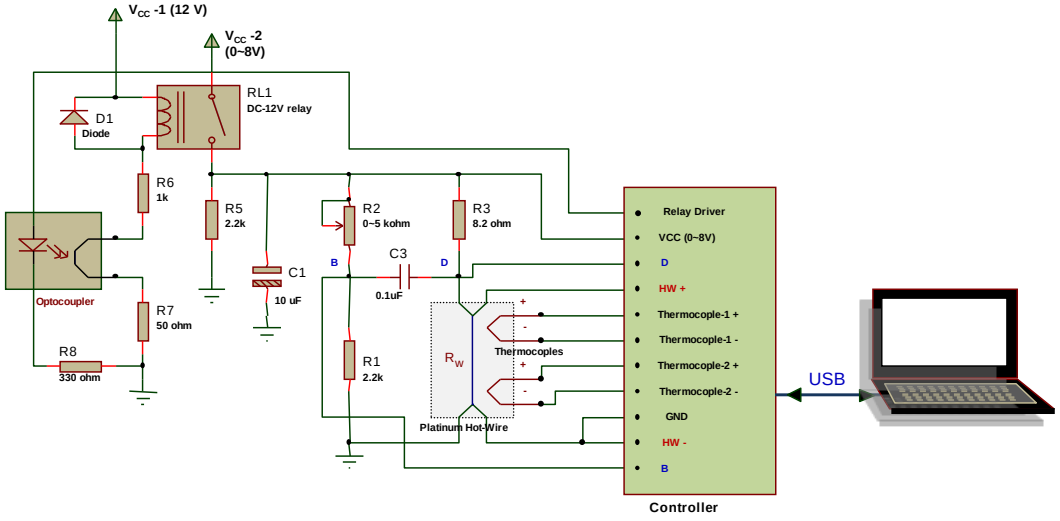

Figure 2. Schematics of electrical circuit with data acquisition system

process and in storage. Polyethylene glycol (PEG) is added and worked both as a size controller and as a capping agent. The four-step preparation scheme for copper nanoparticles starts with dissolving copper (II) sulfate pentahydrate salt, $CuSO_4 \cdot 5H_2O$ (0.01 M), in deionized water to obtain a blue solution. Next, polyethylene glycol 6000 (0.02M) is dissolved in water and added to the aqueous solution containing the copper salt while vigorously stirring. In this step, the solution changes from blue to white. In the third step, ascorbic acid (0.02 M) and sodium hydroxide (0.1 M) are dissolved in water and added to the synthesis solution. Color changes occurred in the aqueous phase from white to yellow. Finally, a solution of $NaBH_4$ (0.1 M) in deionized water is prepared and added to the solution under continuous rapid stirring. An instant color change occurred in the aqueous phase from yellow to reddish brown. The appearance of this color indicated that the reduction reaction has started. The source of electrons for the reaction was BH^{-4}. The mixture is further stirred rapidly for around 10 min in ambient atmosphere, to allow the reaction to complete.

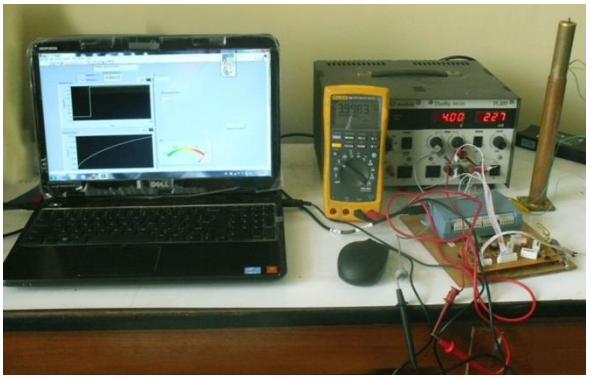

Figure 3.Experimental setup

6. Characterization

The nano suspension solution containing copper nanoparticles is analyzed byUV-vis Spectrophotometer andX-Raydiffractometer(XRD).Small metal nanoparticles exhibit the absorption of visible electromagnetic waves by the collective oscillation of conduction electrons at the surface [4]. This is known as the surface plasmon resonance effect. The interest in this effect is the possibility of using it as a tracer for the presence of metal nanoparticles with a simple UV-visible spectrometer.The plasmon resonance of the synthesized Cu nanoparticles appeared at 562.50 nm as shown in Fig.4.The synthesized Cu nano solution is dried and filtered. Then Cu nanoparticles are analyzed by (RIGAGU – Multiflex 2 kW X-ray diffractometer system) which uses CuK_α(1.5405 Å) as a radiation source operated at 40kV and 20 mA. The XRD pattern is given in Fig.5. The high intense peak for materials is generally (1 1 1) reflection, which is observed in the sample. Two peaks at 2θ values of 43.255 and 50.398 deg corresponding to (111) and (200) planes of copper were observed and compared with the standard powder diffraction card of Joint Committee on Powder Diffraction Standards(JCPDS),copper file No. 04–0836.

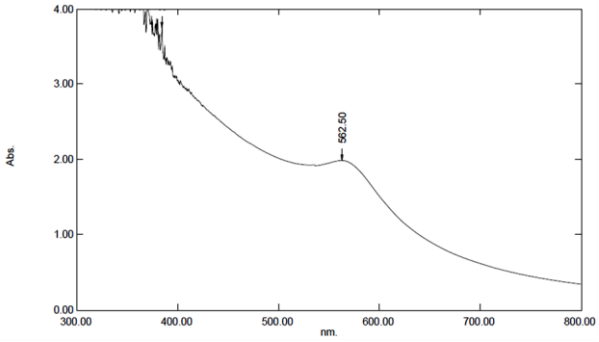

Figure 4.The UV-Visible spectrum of copper colloid solution (after 10 minutes reaction)

The XRD study indicates that the resultant particles are Copper Nanopowder with face-centered cubic (FCC) structure. Considering the peak at degrees, average particle size has been estimated by using Debye-Scherrerformula$= \frac{0.94\lambda}{\beta cos\theta}$,where 'λ' is wave length of X-Ray (1.54056 nm), 'β' is FWHM (full width at half maximum), 'θ' is the diffraction angle and 'D' is particle diameter size. The particle size of synthesized Cu nanoparticle are shown in table 2 and the average particle size is 48.91 nm.

Table 2.Sizes of Cu nanoparticle

Peak Position, 2θ(deg)	d (A°)	Plane (hkl)	FWHM	Crystallite size (nm)
43.255	2.0899	(111)	0.163	54.759
50.398	1.8092	(200)	0.213	43.068
Average				48.91 nm

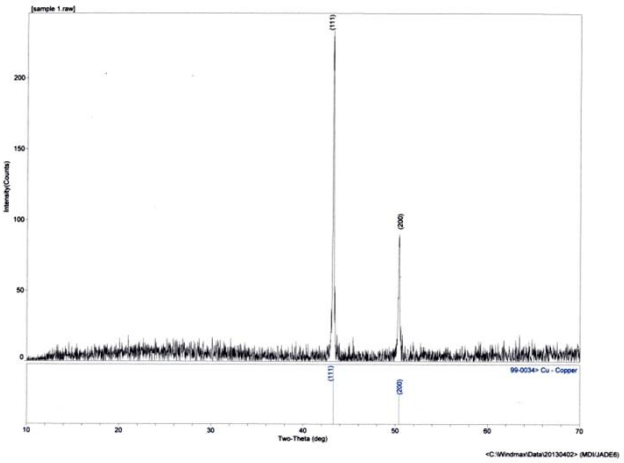

Figure 5 The XRD pattern of copper nanoparticles

7. Results and Discussion

The constructed thermal conductivity apparatus has been calibrated with known samples. Then the thermal conductivity of Cu nanosolution has been measured and compared with the calibrated samples.

Ethylene glycol with 99.9 % purity and deionized water has been used as standard test fluids for over-all calibration of the HWTC apparatus. The measured thermal conductivity of ethylene glycol at 30.0˚C is 0.259 W/m˚C and that of deionized water is 0.605 W/m˚C. The calibrated results are compared with the engineering standard data of each sample and they are described in table 3. The measurement error of the apparatus can be found in acceptable range.

To measure the thermal conductivity of copper nanofluid,firstly, the synthesized nanofluid is centrifuged for 30 min at 1000 rpm. The clear supernatant liquid was discarded and methanol and de-ionized water was added to the centrifuge to wash the surfactant from the surfaces of the particles. The copper powders were then placed in a vacuum dessicator for 2 to 3 days. Nanofluids, of 1 % volumetric nanoparticle concentration, have been prepared by the two-step method, using copper nanoparticles with ethylene glycol as the base fluids[5]. The physical stabilization method of ultra-sonication has been applied to the nanofluids, by placing the nanofluid container in an ultrasonic bath for about 10 hours.

The Cu nanosolutionhave been measured using the calibrated transient HW thermal conductivity apparatus. Since this solution is electrically conductive, it has been prepared very carefully. Moreover, the leakage of current can cause the measurement errors and electric shock for sensors. The conductivity measurement is taken 30 minutes after preparing the sample.

The measurement results are given in Fig.6, Fig.7and Fig.8.The measurement data are linear in logarithmic scale between 1s and 10s. The initial deviation from linear temperature change is due to initial transience. The deviation from linearity at later times, with higher temperature differences, can be attributed to on-set of convection heat transfer and finite boundary effects. The concudtivity of Cu nanosolution is better than that of thedeionized water and glycol solutions and the comparison of thermal conductivities for test fluids are illustrated in Fig. 9. The thermal conductivity of copper nanofluid is 1.23W/m˚C and the relative conductivity ($\kappa_{cu\_nano}/\ \kappa_{water}$) is 2.02 which yields about 50.4% enhancement.

Table 3. Comparison of reference and measured thermal conductivities

Fluid	Reference [W/m°C]	Measured [W/m°C]	Error
Ethylene Glycol (@30.0°C)	0.258	0.259	0.657%
deionized water (@ 30.0°C)	0.609	0.605	0.388%

8. Conclusion

This paper presents the development of thermal conductivity measurement apparatus for nanofluids usingTHW method. This apparatus needs the small volume of liquid samples to measure with better precision and accuracy. The flexible design provides

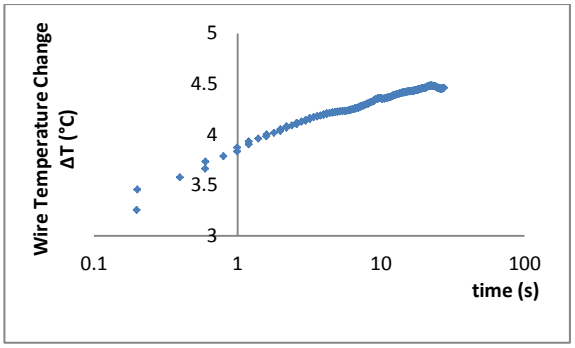

Figure 6 The wire temperature change against time for copper nanofluid

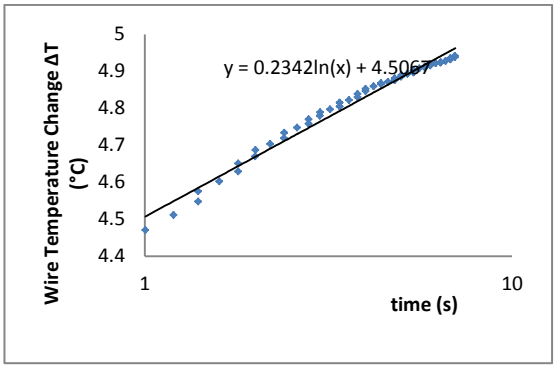

Figure 7 Linear portion of ΔT vsln t

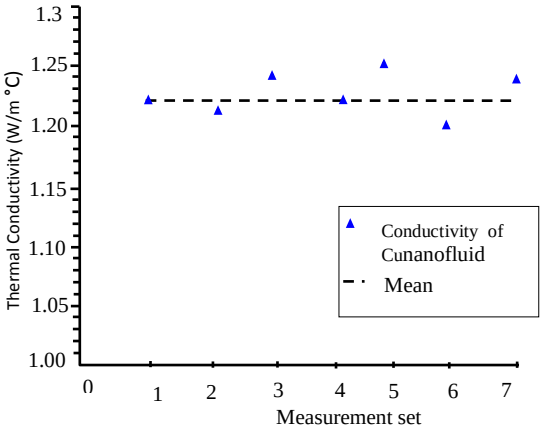

Figure.8Thermal conductivity measurement results of copper nanofluids

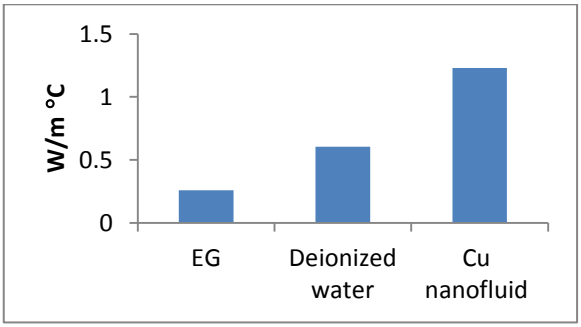

Figure 9.Comparison of thermal conductivitiesfor testfluids

easy calibration and the data acquisition hardware can measure the temperature of the sample with high precision. The data processing algorithm minimizesthe signal noise and enhances acquisition of measurement data.The copper nanoparticle has been successfully synthesized by a chemical reduction method and the thermal conductivity of copper nanofluid has been measured with the developed apparatus.

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