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TECHNICAL NOTE

Design and Fabrication of a Simple and Inexpensive Measurement Probe for the Evaluation of Thermal Conductivity of Nanofluids

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Commercially available tools for thermal conductivity measurement are often costly. Such tools neither allow customization in accordance with the experiment nor permit thorough analysis of the data obtained. Custom made solutions described in the literature are often complex in their design or vague about their fabrication details. Here we report the design and fabrication of a simple and cost-effective thermal conductivity measurement probe based on transient hotwire method which accommodates features like ease of maintenance, durability, portability and the ability to vary the sample size. The instrumentation is automated externally so as to reduce the complexity of the probe further. Accuracy of the probe is tested by measuring the thermal conductivities of standard liquids (deionized water, glycerol and kerosene). The thermal conductivity values of synthesized Fe_3O_4 ferrofluids and TiO_2 nanofluids is measured.

KEYWORDS: Transient Hotwire Method, Nanofluids, Thermal Conductivity.

1. INTRODUCTION

Thermal conductivity of a material is an indispensable and important parameter to characterize while focusing on the performance of heat transfer fluids, particularly nanofluids. To measure the thermal conductivity of a material the following techniques are commonly used: the temperature oscillation method,[1] 3-ω method[2] and the transient hotwire method.[3] The choice of the technique depends on the type of material to be analyzed, its thermal properties, and the temperature range in which the thermal conductivity is to be measured. Among these, the transient hot-wire method has been in vogue and is now widely accepted as being the most reliable.[4]

The transient hot wire method is the measurement of the temperature change with time of a thin wire (preferably of a metal) immersed in the medium of interest, on the application of an electric voltage across it. This technique which was first used to measure the thermal conductivities of solids and gases, is today well established to measure the absolute thermal conductivities of nanofluids for which the uncertainties in measurement reported are below 2%.

Nanofluids[5–7] are a class of heat transfer fluids which are synthesized by dispersing nanoparticles in conventional fluids. Such fluids have garnered interest because of their enhanced thermal conductivities as compared to other heat transfer fluids. The enhancements in thermal conductivity of base fluids on addition of nanoparticles have been reported.[8–11,24] Industries involved in design and manufacturing of heat removal systems for automobiles, high vacuum systems, microelectronic devices, are looking into nanofluids as potential replacement for conventional heat transfer fluids.

Recent interest in nanofluids necessitates the design and development of the thermal conductivity measurement apparatus based on the transient hotwire method. Though the transient hotwire method in itself is easy to implement, the apparatus described in literature[18–21] is often complicated or is oversimplified in its schematics, with no description given about its fabrication. We have applied several design modifications to the hotwire instruments mentioned by Choi et al.,[5] Alvarado et al.[16] and Assael et al.[17] to design and fabricate a simple probe. We have incorporated modifications like the use of copper rods as support cum conducting wires, use of a teflon block with screws for sample size adjustment and a jotter pen's spring to maintain tension on the heating/sensing element (coated platinum wire). These modifications enables cost reduction and simplifies the overall fabrication. Such a custom made probe could benefit laboratories which are looking to initiate research in the domain of nanofluids. Thus, in our work we have designed, fabricated and automated an inexpensive and a simplified thermal conductivity measurement

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probe based on the transient hotwire method. The performance of this instrument is demonstrated by evaluating the thermal conductivity of a few samples of nanofluids synthesized in the author's laboratory.

2. EXPERIMENTAL DETAILS

2.1. Transient Hotwire Method

The transient hotwire method is one of the most commonly used experimental technique for measuring the thermal conductivity of fluids. A hot wire—usually a wire of platinum, is placed in the fluid of which the thermal conductivity is to be measured. The wire serves both as a heating element and a thermometer. The mathematical model is based on the assumption that the wire is infinitely long (suspended in an infinite medium) and is a thin continuous source of heat. The governing equation is based on Fourier's law and its solution subjected to specific boundary conditions.

The relationship thus obtained[12–14] can be approximated as:

$$\frac{d(\Delta T)}{d(\ln t)} = \frac{q}{4\pi k} \tag{1}$$

where q is the heat flux per unit length, k is the thermal conductivity of the medium, ΔT is the temperature change, and t is the time taken for the temperature change to occur. In the experiment, the wire is heated by a constant voltage source and the rise in the temperature over a period of time, of the platinum wire is determined from the change in its resistance. The thermal conductivity can thus be determined from the slope of the ΔT versus $\ln(t)$ curve and the heating power.

2.2. Design and Fabrication

The present design of the thermal conductivity measurement unit is a modified form of those already mentioned in the literature.[15,16,22] As in all the systems, a platinum wire is used as a hot wire which also acts as a temperature sensing element. Some of the systems mentioned in the literature,[23] have made use of a copper tube as a container, but we have preferred a common laboratory glass test-tube so as to visually inspect the nanofluid sample for coagulation during measurement. Instead of steel rods as support and copper connectors as electrodes we have used copper rods (average diameter 1.2 mm) to function both as electrodes and support, which saves space and materials, and simplifies the design further. A "spring and slide" arrangement is coupled with the platinum wire (diameter 0.05 mm, length 10 cm) to maintain a desired strain across it. Spring commonly found in jotter ball pens is used for this purpose. Tension on this spring and on the platinum wire is adjusted with a steel block fitted with a screw. The sliding arrangement makes it possible to vary the sample size from 7 ml to 22 ml. The copper rods are flattened and pierced with minute holes at locations where the platinum wire is to be attached. The copper rods with the platinum

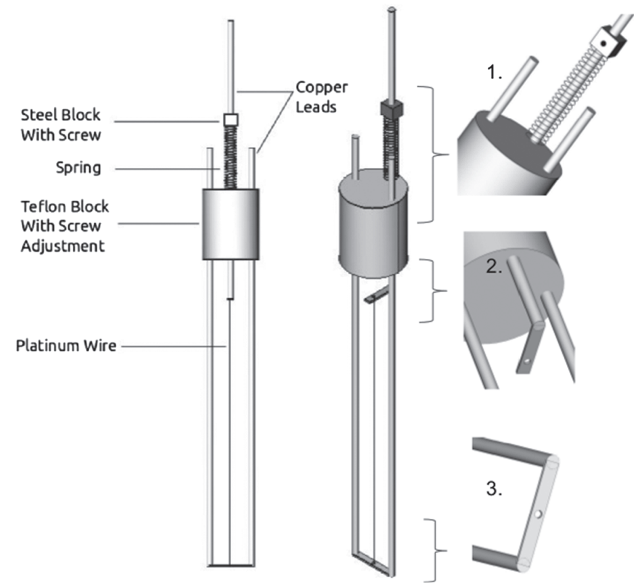

Fig. 1. Schematics of the thermal conductivity measurement probe and the necessary design modifications adapted: 1. Spring and slide arrangement. 2. Flattened hook-shaped rod with a hole. 3. Flattened U-shaped rod with a hole.

wire is mounted on a teflon block with screw adjustments. These modifications are summarized in Figure 1. The 2D sketch with design details along with the actual picture of the probe is shown in the Figure 2.

Any measurement equipment dealing with nanofluids requires frequent cleaning. The simplicity of the design of our thermal conductivity probe makes it easy to maintain and thus ensuring a long shelf life.

2.3. Procedure

The temperature coefficient of resistance (TCR) of the platinum wire is calibrated by measuring its resistance as the temperature of the surrounding medium is varied. The wire resistance versus the temperature is plotted in the Figure 3. The TCR of the platinum wire thus obtained for our probe is 0.00322 $(\Omega/\Omega K)$.

The setup necessary to measure the thermal conductivity of nanofluids mainly consists of the aforementioned probe connected in a three wire configuration with a wheatstone bridge—made of two 1.2 $k \pm 1\%$ Ω resistors and a $100 \pm 5\%$ Ω Trimmer (Pot), a high precision nanovoltmeter (Fluke 8846A)—which is also used as a data logger and a DC voltage supply (Agilent, U8002A) adjusted at 2 Volts (Fig 4).

The wheatstone bridge is manually balanced by applying a small voltage (0.1 V) across it. The source voltage is kept at a desired value, and the voltage across the bridge is measured at regular intervals (4 ms) as the current flows through the circuit. The temperature change of the wire is calculated from the voltage offset data using the following equation (obtained for a Wheatstone bridge) to find the

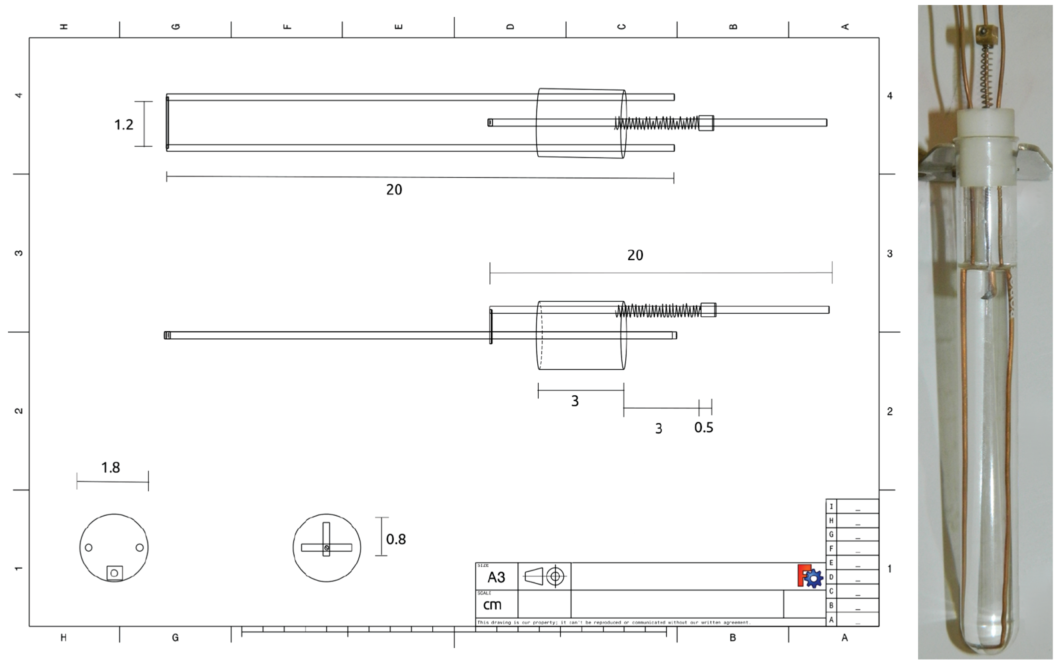

Fig. 2. 2D sketch of the unit's design and picture of the actual probe in a laboratory test-tube (right).

resistance of the wire R_W,

$$R_W(t) = \frac{V_S R_D (R_1 + R_2)}{V_S R_1 + V(t)(R_1 + R_2)} - R_D \qquad (2)$$

where R_D is the resistance of the trimmer (pot), R_1 and R_2 are the resistances of the corresponding fixed resistors, V_S is the voltage supplied to the bridge, and $V(t)$ is the voltage across the bridge.

$$\Delta T(t) = \frac{R_W(t) - R_W(0)}{\alpha R_W(0)} \qquad (3)$$

where α is the temperature coefficient of resistivity of platinum. The measurement time is about 8 seconds and slope of the linear region of ΔT versus ln(time) curve is

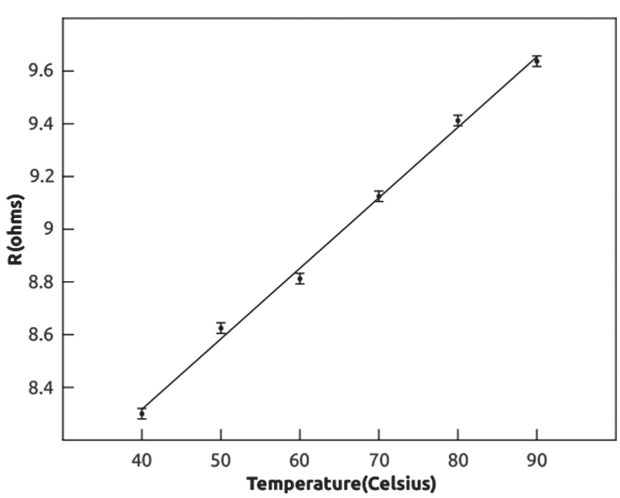

Fig. 3. Calibration of the platinum wire for TCR, with linear fitting: $R = 0.02574T + 7.303$.

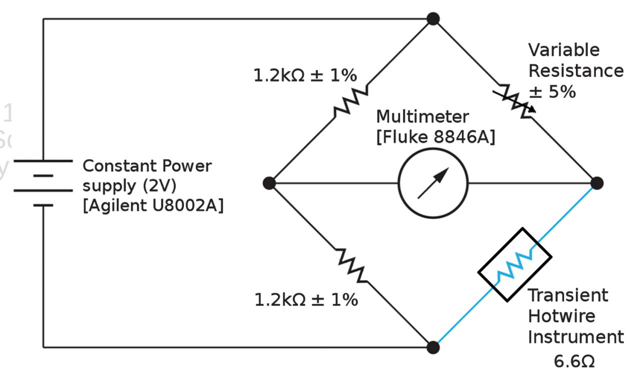

Fig. 4. The thermal conductivity setup.

measured.[5] The thermal conductivity of the liquid is then calculated from Eq. (1).

After every reading, the platinum wire is allowed to cool for 20–30 minutes. The data thus collected at a sampling rate of 4 ms (0.2 PLC, 50 Hz) is then retrieved and analysed using a graphing and analysis software-QtiPlot.

3. RESULTS AND DISCUSSION

The apparatus is calibrated by comparing the experimentally obtained thermal conductivities of deionized (DI) water and glycerol with those from the literature[25] values, at room temperature. The repeatibility of measurements over 10 sets of readings shows a standard deviation of ±0.03 for both glycerol and DI water.

The Fe_3O_4 ferrofluid was synthesized by controlled chemical co-precipitation method.[26,27] In this method, anhydrous ferric chloride and ferrous sulphate heptahydrate are added in the molar ratio of 2:1. 25% of aqueous

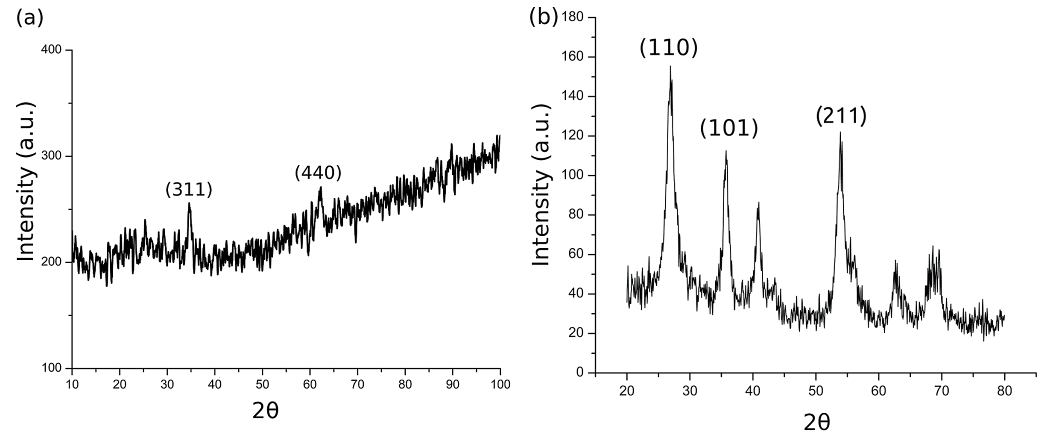

Fig. 5. XRD spectra of (a) Fe_3O_4 and (b) TiO_2 nanoparticles.

ammonia is added dropwise for the oxide to precipitate. The colloidal suspension thus prepared is mixed with oleic acid so as to coat the Fe_3O_4 nanoparticles. This slurry is washed with acetone and dispersed in household grade kerosene using a bath sonicator.

TiO_2 nanofluid was synthesized by a similar co-precipitation route.[28] $TiCl_3$ solution is added to NH_4OH (100 mM) aqueous solution in 1:6 volume ratio. The pH of the solution is increased to 2. The precipitate is separated by centrifugation and then washed in iso-propyl alcohol and dried at 30 °C. The white precipitate thus obtained is dispersed in kerosene using a bath sonicator.

X-ray Diffraction spectra of the dried Iron Oxide and Titanium dioxide samples is recorded using a X-ray diffractormeter (Rigaku D max) at Cu Kα ($\lambda = 1.54$ Å) as shown in Figure 5. The major crystallographic planes are identified using the JCPDS tables. The average grain sizes of the Fe_3O_4 and that of TiO_2 nanoparticles are calculated using the Debye Scherrer's formula:

$$D = \frac{0.9\lambda}{\beta \cos\theta} \tag{4}$$

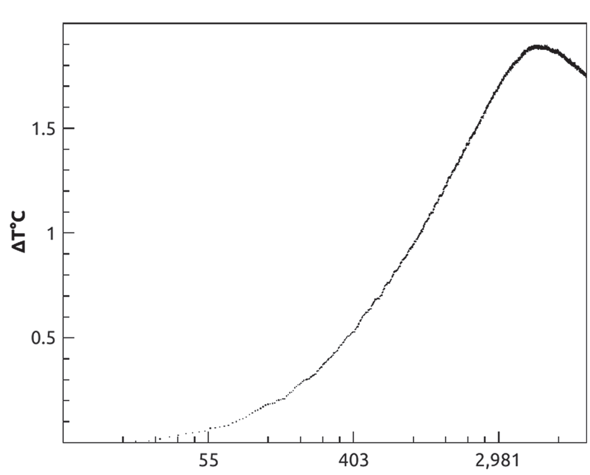

Fig. 6. Temperature change of the platinum wire in kerosene, versus time.

where D is the grain size of the crystallite, λ is the wavelength of the X-rays used, β is the broadening of diffraction line measured at the half of its maximum intensity in radians and θ is the angle of diffraction.

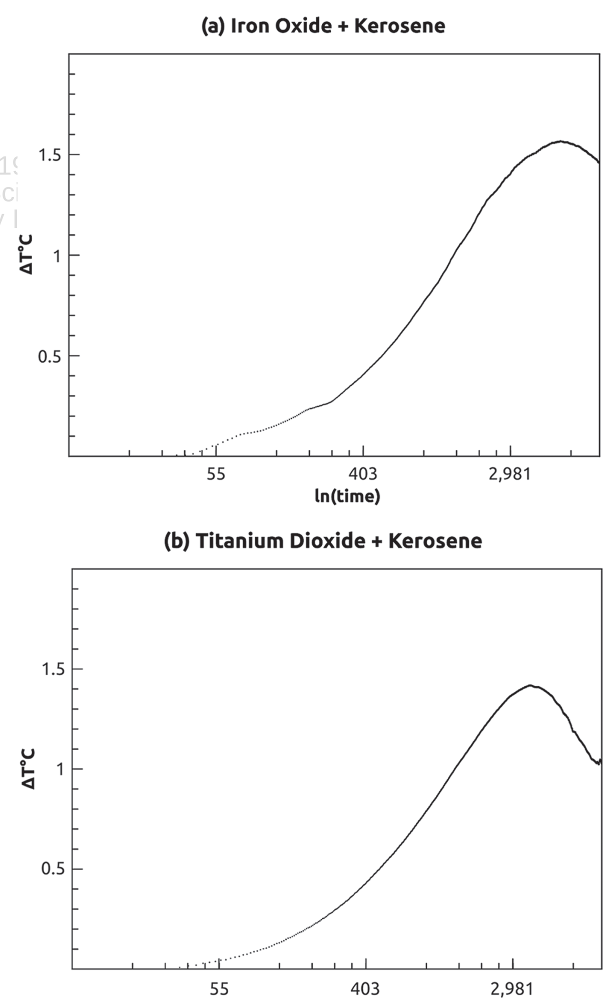

Fig. 7. ΔT versus $\ln(t)$ plot for (a) Fe_3O_4 + kerosene, (b) TiO_2 + kerosene nanofluids.

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Table I. Comparison of thermal conductivity values (of standard liquids and kerosene based nanofluids) from literature with that obtained by the probe.

	Literature[25,29] ($W\ m^{-1}K^{-1}$)	Experiment (with probe) ($W\ m^{-1}K^{-1}$)
Glycerol	0.28	0.29 ± 0.03
Water	0.6	0.55 ± 0.03
Kerosene	0.15	0.16 ± 0.02
Kerosene + Fe_3O_4	0.21	0.22 ± 0.03
Kerosene + $TiO_2^{\#}$	–	0.21 ± 0.02

Note: #No value was found in literature.

This gives the average grain size of the synthesized Fe_3O_4 and that of TiO_2 nanoparticles to be 11.9 nm and 9.8 nm respectively.

The temperature change versus time profiles of kerosene, and kerosene dispersed with Fe_3O_4 and TiO_2 are measured and shown in Figures 6 and 7. The thermal conductivity of Fe_3O_4 nanofluid is measured to be 0.22 (±0.03) $W\ m^{-1}K^{-1}$ which shows an enhancement of 39% over the base fluid-kerosene, comparable to that measured by Yu, et al.[29] The thermal conductivity of freshly dispersed TiO_2 nanofluid gives a 30% enhancement over kerosene.

4. CONCLUSION

A probe based on transient hot wire method has been developed, designed and fabricated to measure the thermal conductivity of water, glycerol, kerosene and kerosene based nanofluids. The objective was to reduce the cost and complexity of the thermal conductivity measurement probes found commercially and in the literature so as to make the probe easy to fabricate, customize and maintain. In achieving this objective, several design factors to accommodate varying sample size (7 ml to 22 ml), adjustment of tension on the platinum wire are included as modifications over the apparatus mentioned in the literature. The design and fabrication details of the thermal conductivity probe are described systematically.

The thermal conductivity probe is calibrated with standard liquids (deionized water, glycerol and kerosene) and the thermal conductivity values of kerosene based nanofluids are measured. Enhancement of 39% and 30% of thermal conductivity values over the base fluid (kerosene) is measured for Fe_3O_4 and TiO_2 nanofluids respectively.

The simplicity of design and inexpensive fabrication of this thermal conductivity probe makes it accessible to high school laboratories.

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