FABRICATION OF TRANSIENT HOT WIRE THERMAL CONDUCTIVITY APPARATUS FOR LIQUIDS

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Abstract: An attempt has been made for making an improved Hot Wire Thermal Conductivity apparatus for thermal conductivity measurements of common fluids as well as nano fluids. A platinum (Pt) wire of 50.8 μm diameter with a Teflon insulation coating of 25.4 μm thickness was used as the hot-wire heater and temperature sensor for the present application. The present apparatus finds solutions for easy calibration of uniform Pt-wire tension and thus reducing the strain effect on temperature measurement, measurement of Pt-wire voltage drop independently from power wiring (four wires) and an effective off-centered mechanical design to minimize the test fluid sample size, but at the same time providing additional space for wiring, including three inside thermocouples for fluid temperature uniformity verification.

The bias measurement error, based on calibration with common fluids has been found to be within 1.5 %, and precision, i.e., repeatability error within 2.5 %.

Keywords: Thermal conductivity, heat transfer, liquids, nano fluids, transient hot wire method

1.INTRODUCTION

In general, during any period in which temperatures change in time at any place within an object, the mode of thermal energy flow is termed transient conduction. Unsteady-state situations appear after an imposed change in temperature at a boundary of an object. They may also occur with temperature changes inside an object, as a result of a new source or sink of heat suddenly introduced within an object, causing temperatures near the source or sink to change in time.

The mathematical model for the hot-wire 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[1].

It is 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 is derived from the Fourier's equation for one-dimensional (1-D) 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, and ΔT is the temperature difference between the medium and initial temperature. The Eq. (1) is the subject of the following boundary conditions[3]:

$$\lim_{r\to 0}\left\{r\left(\frac{\partial T}{\partial r}\right)\right\} = -\frac{q}{2\pi k_f} \qquad \text{at t=0 and r=0} \tag{2}$$

$$\lim_{r\to\infty}\{\Delta T(r,t)\} = 0 \qquad \text{at } t\geq 0 \text{ and } r=\infty \tag{3}$$

Where, ρ_f and C_f are density and specific heat capacity of the test medium, respectively. After initial, short transient period , except for the first term containing time *t*, the higher order terms could be neglected, resulting in a very good approximation as,

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

where γ =0.5772 is the Euler's constant. For constant fluid medium properties and a fixed and arbitrary radius *r*, after differentiation of Eq. (4), the radius is eliminated from the equation, and the following relation is obtained,

$$k_f = \frac{q}{4\pi}\frac{1}{d(\Delta T)/d\ln(t)} \tag{5}$$

Therefore, if temperature of the medium is measured as function of time at any fixed radial position, including at the contact with the line source (i.e. the temperature of the 'thin' line source), the thermal conductivity of the test medium, k_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, see Eq. (5). The advantage of the hot-wire method is its simplicity and consequently low cost of construction [4].

2. LITERATURE REVIEW:

Kostic.et.al [1-2] has been developed transient hot-wire thermal conductivity apparatus to measure the thermal conductivity of fluids, polymer solution, nanofluids and poly-nano fluids (a mixture of nano particles, polymers and conventional heat transfer fluids)[5].

An apparatus based on the single, transient hot-wire method has been developed, designed and fabricated with main objective to measure thermal conductivity of fluids, polymer solution. The goal was to reduce the overall test sample volume for fluids, while maintaining the precision and accuracy of the apparatus. The new apparatus employs innovative solutions for easy calibration of controlled platinum, hot-wire tension, and thus minimizing the strain influence on temperature measurement (i.e., minimizing the well-known and unwanted "strain-gage effect" on Pt-wire electrical resistivity); measurement of Pt-wire voltage drop independently from power wiring (four wires) and an effective off-centered mechanical design to minimize the fluid sample size.

3. Experimental setup:

Glass Tube:

Glass tubes or glass tubing are hollow pieces of borosilicate or flint glass used primarily as laboratory glassware. Glass tubing is commercially available in various thicknesses and lengths. Glass tubing is frequently attached to rubber stoppers.

Teflon Coated Nichrome Wire:

Nichrome resistance wire is coated with DuPont Teflon to create a non-stick surface for use in all types of high-temperature sealing equipment.

Temperature Sensing Element (PT100):

Platinum resistance thermometers (PRTs) offer excellent accuracy over a wide temperature range (from-200 to +850 °C). Standard Sensors are available from many manufacturers with various accuracy specifications and numerous packaging options to suit most applications. Unlike thermocouples, it is not necessary to use special cables to connect to the sensor.

TEFLON FOR SEALING:

PTFE is used as a non-stick coating for pans and other cookware. It is very non-reactive, partly because of the strength of carbon–fluorine bonds and so it is often used in containers and pipework for reactive and corrosive chemicals[7]. Where used as a lubricant, PTFE reduces friction, wear and energy consumption of machinery. It is also commonly used as a graft material in surgical interventions.

T-Type Thermocouples:

Type T (copper – constantan) thermocouples are suited for measurements in the −200 to 350 °C range[8].

Hot Wire Cell Apparatus:

The cell design was aimed to reduce the test sample volume of nano fluids, and at the same time, to provide a controlled tension in the hot-wire during heating and thermal dilatation. Some of the important design factors that have been considered are: controlled tension of the hot-wire, flexibility in handling and cleaning, suspension and centering of the platinum hot-wire, connections of the leads to the hot-wire, electrical wire routing, temperature measurement of the sample, and electrical and signal wiring connections.

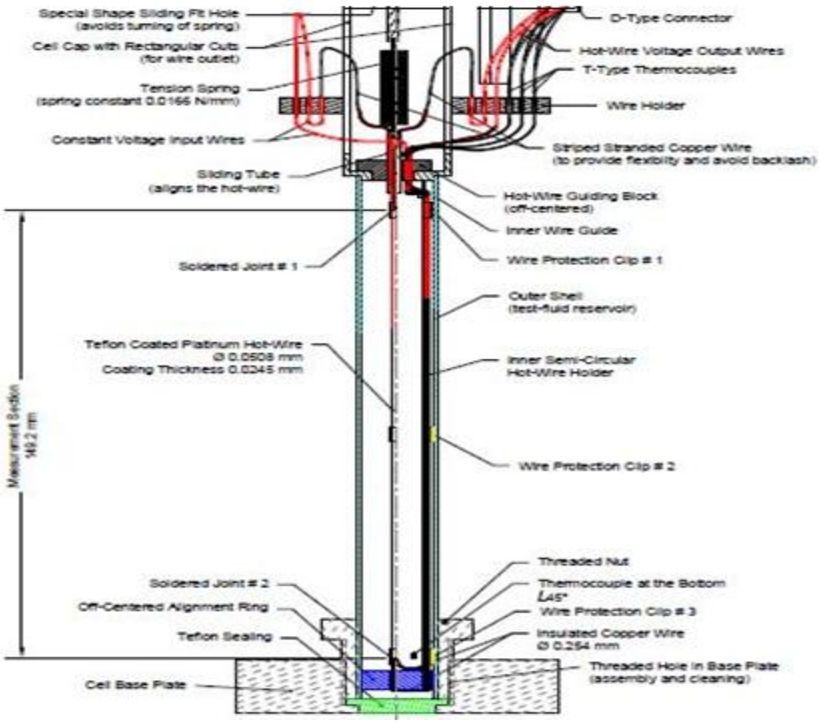

Fig:3.1 Cross sectional view of transient hot wire thermal conductivity apparatus

Platinum has been selected as superior hot wire material. It has higher thermal conductivity (TC) compared to the nichrome and tantalum, also used as hot-wires. Along with the material, hot-wire radius is one of the most important parameters for the cell design.

A cross sectional view of the newly designed hotwire thermal conductivity apparatus with major mechanical components is shown in Fig. 3.1. The major assembly components of the apparatus' cell are: base plate, outer shell, and cell cap with hot-wire. The cell base plate with a threaded hole at the center of the plate (sealed by a Teflon washer) is used for convenient assembling and disassembling the outer shell. The outer shell with 17.4 *mm* inner diameter 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 hot-wire holder with an alignment ring is soldered at the lower end at an offset. A hot-wire 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 (i.e., sliding tube, tension spring, spring rod and locking nut). Two copper wires at the top soldered-joint of the platinum hot-wire are passed symmetrically through a sliding tube. The inner hollow portion of the sliding tube is filled with epoxy to couple the copper wires with the sliding tube. A clearance between the sliding tube and hot-wire guiding block hole ensure near frictionless motion of the sliding tube. The spring rod is specially shaped to have external threads. An inverted L-shaped gauge has been seated on the holder for calibrating the hot-wire tension and guarding the spring rod movement. One of the two copper wires at another soldered joint of the platinum hot-wire is passed through the off-centered hole of the alignment ring, while the other has been guided through a hole in the inner semi-circular hot-wire holder. The copper wires at the alignment ring act as fixed rigid ends of the hot-wire.

Fig:3.2 Transient hot wire thermal conductivity apparatus

The main design parameters are:

- material of hot-wire,
- radius of hot-wire,
- insulation coating,
- length of hot-wire,
- radius of the test sample outer boundary,
- length of the sample.

Platinum has been selected as superior hot wire material. It has higher thermal conductivity (TC) compared to the nichrome and tantalum, also used as hot-wires. Along with the material, hot-wire radius is one of the most important parameters for the cell design. Among commercially available sizes, 25.4 and 50.8 μm radius platinum-wires have been selected for the present application, since smaller 12.5 μm radii is considered to be too fragile for cleaning and handling of nanofluid samples[9]. Teflon has been selected as insulating material, as it is highly resistant to chemical reactions, corrosion and stress-cracking at high temperatures. A 50.8 μm diameter platinum wire with a Teflon insulation coating of 25.4 μm thickness has been used as the hot-wire. Care has been taken to avoid any disruption of the coating during hot-wire mounting.

In our design, the length of the platinum hot-wire was taken as Lw = 0.1484 m, based on the 0.139 m minimum length of hot-wire[10].

According to the ideal model of this instrument, an infinitely long, line source of heat possessing zero heat capacity and infinite thermal conductivity is immersed in an infinite isotropic material, with physical properties independent of temperature and in thermodynamic equilibrium with the line source at time t = 0 at a temperature T_0. The heat transferred from the line source to the sample when a stepwise heat flux q, per unit length is applied, is assumed to be entirely conductive. Then the temperature rise of the material at a radial distance, r_0,which it transpires, is the same as the temperature rise at the surface of a wire of radius r_0, is $T_1(r_0, t)$ is given by:

$$\Delta T(r_o,t)=T(r_o,t)-t_o=\frac{q}{4\pi\lambda}\left[\ln\left(\frac{4at}{r_o^2}\right)+\frac{r_o^2}{4at}+........\right]$$

In the above equation, C is a known constant. The equation suggests that, provided the radius of the wire is chosen small enough so that the second term on the right-hand side of equation is negligible, the thermal conductivity of the fluid can be obtained from the slope of the line T_1vs. $\ln t$. Any practical implementation of this method of measurement inevitably deviates from this ideal model[12]. The success of the technique, however, rests on the fact that by proper design, it is possible to construct an instrument that can operate very closely to the ideal model, while at the same time small departures can be treated by a first-order analysis.

In the case of fluids, the instrumentation generally involves a wire some 7 µm to 25 µm in diameter (in order to reduce the correction owing to its heat capacity) and some 150 mm long. The wire is mounted vertically in a cylindrical cell containing the test sample. Often, a second wire differing only in length is employed to compensate automatically for effects at the ends of the wires via the electrical measurement system, but this can also be accomplished with potential taps. Whenever possible, platinum is used for the wire material because its resistance/temperature characteristics are well known and it can be readily obtained in the form of wires with a diameter as small as 5 µm. When the material under test is electrically conducting, it is necessary to insulate electrically the wire from the fluid. A variety of techniques have been employed for this purpose that enjoy different degrees of success depending on the range of conditions to be studied. Near ambient temperature over a range of pressures, it has been found adequate to use a tantalum wire as the sensor that is electrolytically anodized to cover the wire with an insulating layer of tantalum pentoxide 100 nm thick. Under more aggressive conditions, it has been necessary to employ ion-plating of the wire with a ceramic to secure the isolation. In either case, the theory has been modified by the addition of a small correction.

In the case of solids, the need for the wire to be straight and vertical is removed by virtue of the rigidity of the material. The transient hot-wire technique has a unique advantage among transient methods that the thermal conductivity of the test material can be evaluated directly from the slope of the line relating the temperature rise of the wire to the logarithm of time. The heat capacity and density of the test material are required only to evaluate small corrections. Furthermore, the exact dimensions of the heating element and the cell are also unimportant so that the method avoids the intricate alignment problems of the parallel-plate technique while securing absolute measurements of the property. Despite these advantages and its wide application to measurements in gases, solids, and liquids, there has been no commercial development of an instrument of this kind, presumably because of the delicacy of the long, thin wire in the case of devices for fluids, and the difficulty of sample preparation for solids [13].
Precision measurements of resistance can be made by using a four lead technique or by using a Wheatstone bridge. End effect compensation is provided by placing the long hot wire in one working arm of the bridge and a shorter, compensating wire on the other. Each arm of the bridge is designed to be 100 two arms R_1 and R_2 are standard resistors. The resistance in each of the other arms R_3 and R. The leads are roughly $6\ \Omega$ at room temperature and $2\,\Omega$ when the cell is at 76 K. The ballast resistors allow each working arm to be adjusted to a value of 100 Ω.

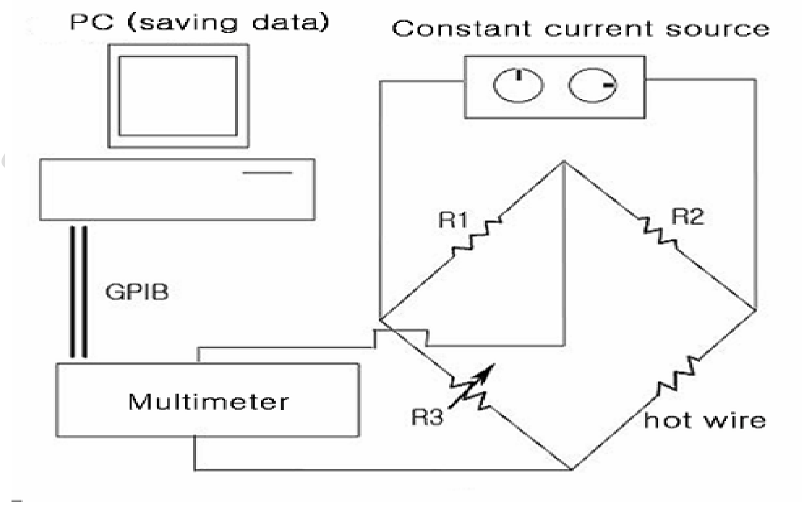

Fig : 3.3 Schematic diagram of transient hot wire method for measuring thermal conductivity of fluids

Measurement Procedure:

- The wire is heated with electrical constant power supply at step time.
- The wire simultaneously serves as the heating element and as the temperature sensor.
- The change in resistance of the wire due to heating is measured in time using a Wheatstone bridge circuit.

- The temperature increase of the wire is determined from its change in resistance.
- Thermal conductivity is determined from the heating power and the slope of temperature change in logarithmic time.

4. RESULTS:

To establish the reliability of the thermal conductivity measurement, calibration experiments were performed for water and Ethylene Glycol at room temperature and compared with the standard values available from the literature. We have also calculated the thermal conductivity for a composite solution of 50% Ethylene Glycol, 50 % of water and brine solution (Nacl solution).

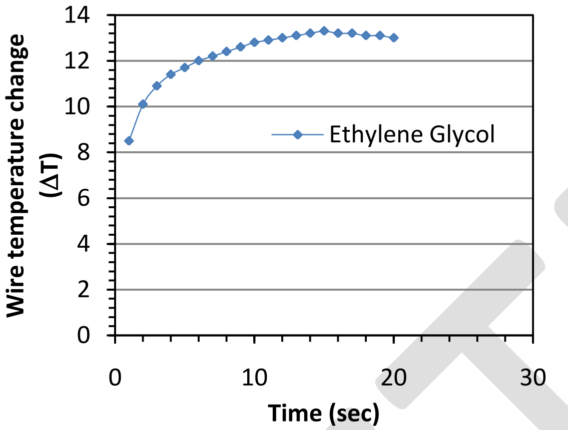

Fig: 4.1 Change of wire temperature with time (EG as liquid)

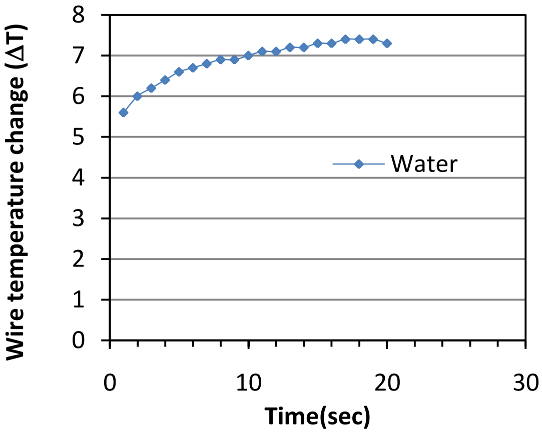

Fig: 4.2 Change of wire temperature with time (water as liquid)

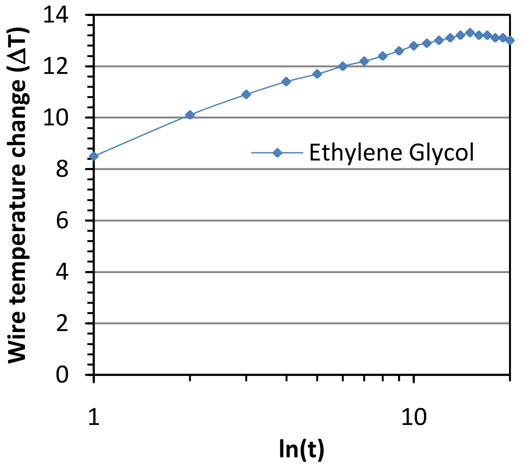

Fig: 4.3 Change of wire temperature vs ln(T) (EG as liquid)

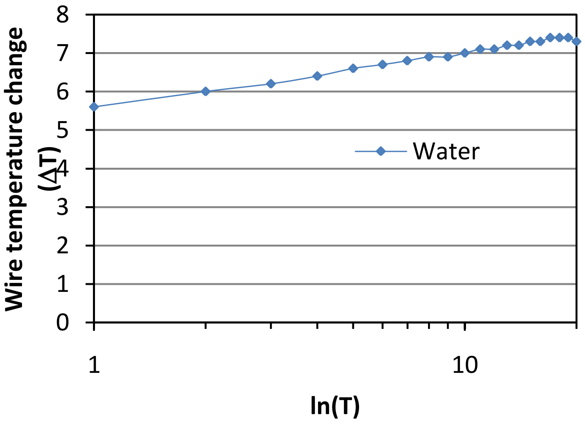

Fig: 4.4 Change of wire temperature vs ln(T) (water as liquid)

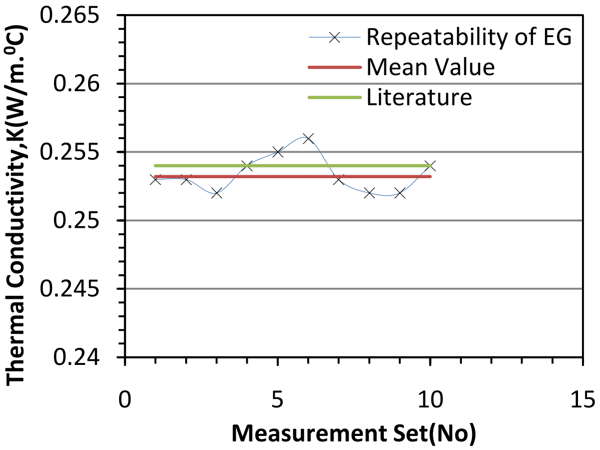

Fig: 4.5 Repeatability of thermal conductivity of EG

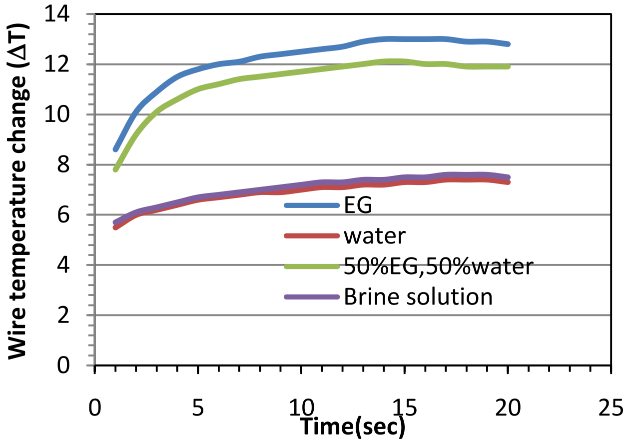

Fig: 4.6 Change of wire temperature with time for different liquids.

Time (sec)	EG (^{0}C)	Water (^{0}C)	50%EG, 50%water (^{0}C)	Brine Solution (^{0}C)
1	8.6	5.5	7.8	5.7
2	10.1	6	9.2	6.1
3	10.9	6.2	10.1	6.3
4	11.5	6.4	10.6	6.5
5	11.8	6.6	11	6.7
6	12	6.7	11.2	6.8
7	12.1	6.8	11.4	6.9
8	12.3	6.9	11.5	7
9	12.4	6.9	11.6	7.1
10	12.5	7	11.7	7.2
11	12.6	7.1	11.8	7.3
12	12.7	7.1	11.9	7.3
13	12.9	7.2	12	7.4
14	13	7.2	12.1	7.4
15	13	7.3	12.1	7.5
16	13	7.3	12	7.5
17	13	7.4	12	7.6
18	12.9	7.4	11.9	7.6
19	12.9	7.4	11.9	7.6
20	12.8	7.3	11.9	7.5

Tab: 4.1 Change of wire temperature for different liquids.

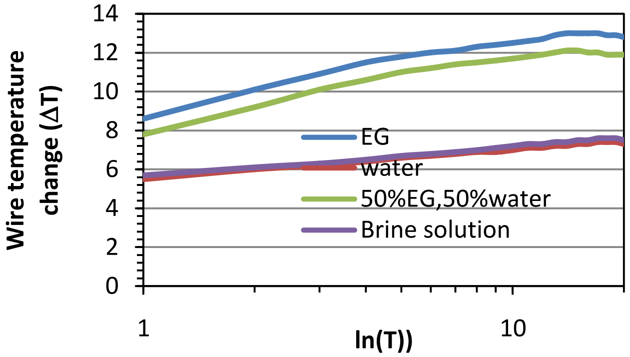

Fig: 4.7 change of wire temperature vs ln(T) for different liquids.

5. CONCLUSIONS:

The time window corresponds to the optimum overall sensitivity where the correlation between all the sensitivity coefficients is minimal.

1. The bias measurement error, based on calibration with distilled water and ethylene glycol, has been found to be within 1.5 %, and precision, i.e., repeatability error within 2.5 %.
2. Thermal conductivity for the composite liquid(50% EG and 50% water) is 4.35
3. Thermal conductivity for the composite liquid(brine solution) is 0.754

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