Development and Calibration of Modified Parallel Plate Method for Measurement of Thermal Conductivity of Liquids: A Review

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Abstract - *Determining the thermal conductivity of liquids is an important in many advanced engineering applications. The conductivity of liquid plays an important role in the design of a variety of engineering applications, such as heat exchangers, power generation, air conditioning, transportation, and microelectronics due to the heating and cooling processes involved. It is desirable to increase the efficiency of heat transfer devices used in these fields, since in case of such an improvement, it becomes possible to reduce the size of the devices and decrease the operating costs of the associated processes. The concept of this paper was to develop a method for measuring the thermal conductivity of liquids. In this article, the authors describe details of the experimental apparatus, testing procedure, data reduction. The purpose of this work was to explain the theoretical bases required for measuring the thermal conductivity of liquids and to develop a method which can be applied in Heat and mass transfer laboratory. In this paper concentrating on the measurement techniques of the thermal conductivity of liquids. Here introduced modified parallel plate method to determine the thermal conductivity of liquids. In the experimental setup used a guarded hot plate method instead of guard heater replaced by whole assembly with good insulator. A good arrangement and experiment procedure is explained. The experimental set-up, testing procedure, and calibration are simple and straightforward.*

***Key Words*: Parallel plate method, liquids, thermal conductivity, experimental procedure, calibration.**

1. INTRODUCTION

In engineering applications liquid properties are required for accurate prediction of their behaviour as well for design of components and systems. The physical properties of liquids, such as thermal conductivity, density, viscosity play an important role in the designing and optimizing a wide verity of engineering applications or process involving heat transfer, such as heat exchangers. In the world of engineering there is a need to quantify how good or bad materials are at conducting heat. For example, let's take a classical shell and a tube heat exchanger, where we have a liquid of higher temperature inside the tube and on the outside is a liquid of lower temperature. To calculate the parameters necessary for designing the heat exchanger, we need to know how well heat transfers from one fluid to another and one of the most important properties is thermal conductivity [1-2].

2. Measuring thermal conductivity of liquids

Thermal conduction is significant topic in the study of heat transfer. Conduction is the transfer of energy from energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, or gases. In gases and liquids, conduction is due to the collision and diffusion of the molecules during their random motion .The thermal conductivity is the property of materials and is defined as the ability of the materials to conduct the heat through it. The rate of heat conduction is proportional to the area and the temperature difference, and inversely proportional to the thickness of the material. The constant of proportionality is the thermal conductivity. Thus, the thermal conductivity, 'k', of a material is defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference. Therefore, it is a measure of how fast heat will flow in the material. A large value for thermal conductivity indicates that the material is a good conductor, while a low value indicates that the material is a poor conductor or a good insulator. The thermal conductivities of materials vary with temperature. This variation, for some materials over certain temperature ranges, is small enough to be neglected. However, in many cases, such as liquids and gases, the variation of the thermal conductivity with temperature is significant [3].

From Fourier's law, it can be seen that, if we know steady-state one dimensional heat flux and measure temperature from two locations and from its difference, thermal conductivity can be calculated.

$$K = \frac{Q/A}{\Delta T/\Delta X}$$

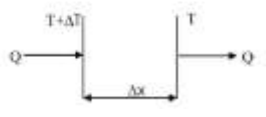

Fig.1 Principle of heat conduction

In practice, there are a few problems. First of all, a one-dimensional temperature field is difficult to achieve, even in homogenous solids. Secondly, with a liquid, which is the topic of this work, there is the ever-present convection current. Convection would increase heat transfer and have an effect on the measured temperature difference, which would in the end, give a wrong value for thermal conductivity. In all thermal conductivity measurements convection should be suppressed. To minimize its effect we should avoid temperature gradients in vertical directions (gravity), or if it's needed, it is better to put the heater on top of a liquid than on the bottom, because of the buoyancy. Likewise, we should avoid larger temperature differences in the field and do the measurement as fast as possible. Even though convection is ever-present in fluids during the heat transfer, by proper design of the method it can be neglected. In all of the existing methods the main focus was on minimizing the effect of convection.

3. Thermal conductivity Measurement for liquids

The methods for measuring thermal conductivity of liquids can be separated into three parts:

1) Steady state methods (coaxial cylinders or parallel plates)

2) Transient state methods (Hot wire, flat plate stepwise heating method and 3ω method)

3) Laser flash method

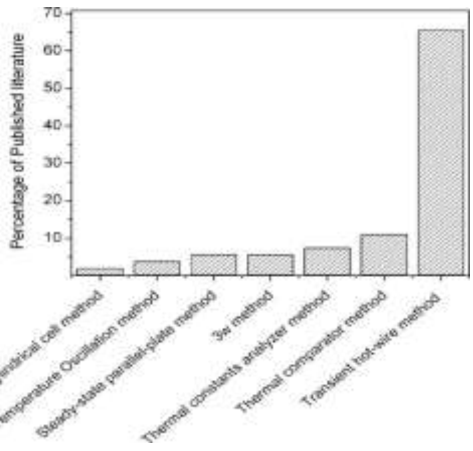

Fig.2 Comparison of the thermal conductivity measurement techniques for liquids.

1. Steady state methods

- Difficult to avoid the effect of convection
- Longer period of measuring time

1.1. Parallel plate method

A small amount of fluid is placed between two parallel round pure copper plates. As the total heat supplied by the main heat flows between the upper and lower plate, the thermal conductivity of the liquid can be calculated from Fourier's law. To assure that there is no heat loss between the liquid and its surroundings, guard heaters are used to maintain a constant temperature of liquid [4].

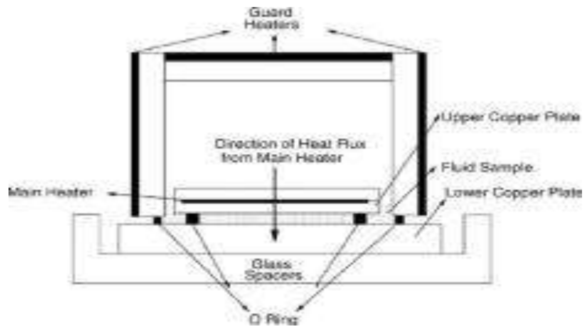

Fig.3 Experimental set up for steady-state parallel-plate method

1.2. Coaxial cylinders method

A liquid is placed in the space between the two concentric cylinders. The inner cylinder is made from copper and in the inside electrical heater is placed. The outer cylinder is made from galvanized material and the back and the front side of the equipment are insulated to nullify the heat loss during the measurement. Two thermocouples are used to measure the outside surface temperature of cylinders. The required measurements for thermal conductivity are the temperatures from thermocouples, the voltage and the current of the heater.

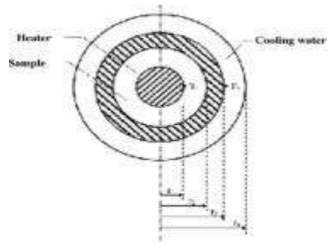

Fig.4 Coaxial cylinders method

2. Transient state methods

2.1. Hot wire method

The hot wire method uses the temperature response of liquid to determine its thermal conductivity. The heat source is a thin platinum wire which is subjected to an abrupt electrical pulse. The temperature of the wire rises and is measured by the same wire which is used as a thermometer. The temperature rise is measured during a short period of time and depends on t. cond. of liquid. The thin platinum wire is used as a heater and a sensor in the closed cylinder, thermal conductivity is defined from the temperature rise in wire. For electrically conductive liquids a mercury filled glass capillary is used [5].

- Very short time of measurement (typically up to 1 second)
- Amount of liquid is usually not small
- Convection is liable to appear, although measurements are short, it's hard to determine when convection starts to appear

The typical diameter of cylinder is around 20mm and wire 0.5mm, the temperature difference is around 4K.

2.2. Flat plate stepwise method

The flat plate above the sample liquid is heated step by step with electric current and the thermal conductivity of liquid is determined from the liquid temperature rise

- Temperature distribution in the sample fluid is uniform, because of the small liquid sample
- Convection is unlikely to appear, measurement time is very short
- Method is not suitable for measuring high electrically conductive fluids

2.3. 3ω method

In 3ω method, a metal strip is used as a heater and as a thermometer. This method is relatively fast and heats a small volume of liquid, so small samples can be used (in literature I have found a thermal conductivity measurement of 12 nl liquid). Also, short measurement time helps to minimize convection and radiation. Theory of 3-omega method is more complicated to understand, but can be explained in a few words: When an alternating current (AC) is used to excite the heater at a frequency 1ω which makes the temperature of the strip to oscillate at 2ω due to Joule heating, this leads to third harmonic (3ω) in the voltage signal. By monitoring 3ω component of the voltage, $V_{3\omega}$, over the heater, the temperature oscillation can be measured, from which thermal conductivity can be calculated.

I have been researching and developing this method with MIKES and currently, the thermal conductivity of water drop has been successfully measured. The heater size used was 50 µm wide and 3 mm long with dielectric layer made from Al_2O_3 which is 135 nm thick [6-7].

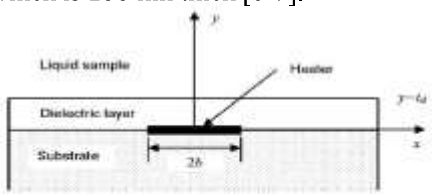

Fig.5 Schematic diagram of the 3 – ω technique for measuring the thermal properties of liquids

3. Laser flash method

A laser beam is used as a heat source of very short duration. The sample liquid is pressed between metal disk, which receives the laser beam energy, and a sample holder. The thermal conductivity is measured from the temperature fall of the front surface of the metal disk and the measurement of the heat discharge into the liquid layer [8-10].

- This method can be applied to liquids of high electrical conductivity
- Desirable method for liquids at higher temperatures
- Convective heat transport is minimized

4. Modified parallel plate method for Measuring thermal conductivity of liquids

We are introduced a new proposed experimental set up to determine the thermal conductivity of fluids. We are used a guarded hot plate method instead of guard heater replaced by whole assembly with good insulator. A good arrangement (proposed experimental set up) and experiment procedure is found from experimental set up and procedure in the literatures review explained. Details of the experimental apparatus, testing procedure, data reduction are presented.

In this proposed experimental apparatus main objective is the liquid is stationary. In the presence of temperature variations and in the presence of gravity the liquid will start moving around due to natural convection. There are two ways of immobilizing the fluid: a) Use a thin layer of the fluid in the direction of temperature gradient is very small and the regime is conduction dominant b) Set up the temperature field in the fluid such that the hot part is above the cold part and hence the layer is in the stable configuration. The plate apparatus is suitably modified to achieve these two conditions. The thickness of the layer is chosen to be very small (of the order of an mm) so that heat transfer is conduction dominant.

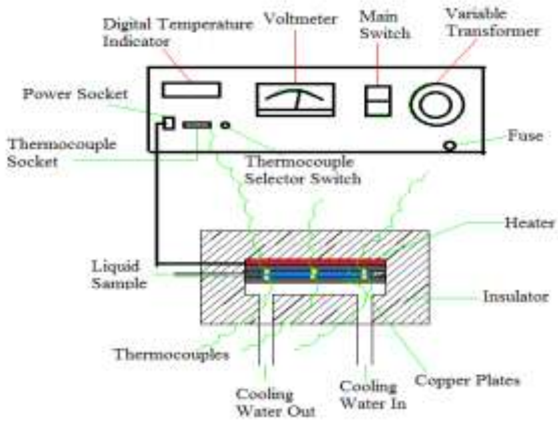

Fig.6 Modified parallel plate method

The thermal conductivity measuring instrument consists of two copper plates in between thin layer of liquid sample is placed, who's thermal conductivity is to be measured. The nichrome heating plate (heater) is placed on upper side of the copper plate. Cooling arrangement is provided from lower side of the copper plate. The thermocouples are mounted on the hot plate side and cold plate side to measure the varying temperature. And lower the whole assembly the insulator is provided.

1.1. Experimental procedure

The electric supply is provided to the heater, when power supply is switched on then heater gets heated. The amount of heat generated is given by Q = V x I. Then the heat is transferred to downward direction through liquid layer and is removed by cooling arrangement is provided from lower side. Now, with the help of Fourier's law of heat conduction the thermal conductivity can be measured.
Thermal conductivity of liquid is given by

$$K = \frac{-Qc\ dx}{A\ dT}$$

Where dx = thickness of liquid layer
dT = temperature difference between hot and cold plate
Qc = Heat conducted through the liquid layer
Qe = Electrical heat input
= V x I.
Qc = Heat conducted through the liquid layer
Qi = Heat loss between the heater and insulator
Qc = Qe - Qi

Where dx = thickness of liquid layer
dT = temperature difference between hot and cold plate

5. Heat loss between the heater and insulator (Incidental heat loss)

Before utilising the unit in order to measure the thermal conductivity of a fluid (liquid or gas), the unit must be calibrated. This is because not all the power input is transferred by conduction through the test fluid, some energy (incidental heat transfer) will be lost to the surroundings and some will be radiated across the set up. In this calibration process, we generate a curve that characterises this incidental heat loss. The incidental heat transfers in the unit are determined by using water (whose thermal conductivity is well known and documented) in the cavity provided between plate.

The determination of the incidental heat transfer (Qi) is find with the procedure explained below. The known conductivity of liquid is transferred in the apparatus and calibration is taken out [11].

1.1. Calibration procedure:-

The following is a brief summary of the procedure to carry out the calibration of the unit:
1. Set up the equipment and make the necessary connections;
2. Pass water through the spacing between copper plate.
3. Switch on the electrical supply;
4. Adjust the variable transformer to give about 10V;
5. At intervals, check the temperature of the hot plate side (Th), and cold plate side (Tc), and when they are stable, record their values and also the voltage;
6. Repeat steps 4 and 5 for 20V, 30V, 40V, 50V and 60V.

1.2. Calculations

The calculations are determined as follows:
1. Find the thermal conductivity of the water, at the average temperature, Tave = (Th + Tc)/2. Temperature-dependent thermal conductivity values for water are found in any heat transfer textbook, such as Incropera and DeWitt, as well as Heat and mass transfer data book, New age International Publisher.
2. Calculate the rate of heat conducted through the liquid layer, *Qc,* from Fourier's Law, i.e.

$$Q_C = KA \times \frac{\Delta T}{\Delta X} \quad (1)$$

Where the area is A = 0.0176, the liquid layer thickness is dx = 0.4 mm, and the temperature difference is $\Delta T = T1 - T2$.
3. Calculate the rate of electrical heat input, *Qe*, from:

$$Q_e = V \times I \quad (2)$$

Where V is the voltage and I is the current
4. Find the incidental heat transfer, *Qi*, (loss, radiation, etc). The incidental heat transfer is the difference between the electrical heat input and the heat conducted through the fluid in the radial clearance, i.e.:

$$Q_i = Q_e - Q_c \quad (3)$$

From the measured data and the results obtained above, a calibration curve of the incidental heat transfer, *Qi*, against the average temperature, Tave, can be generated. Figure presents the calibration curve. As can be seen from the figure, the incidental heat transfer increases linearly as the average temperature increases.

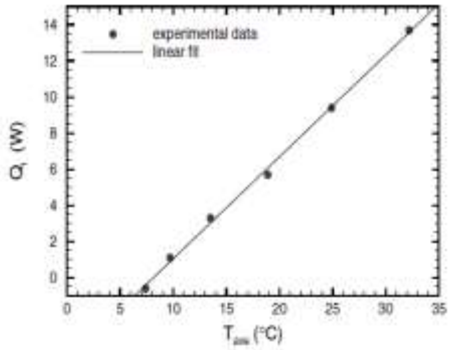

Fig.7 The calibration curve

6. Conclusion

In this paper presented a brief review of the different techniques for the measurement of thermal conductivity of liquids available in literature. The review shows that the most commonly used technique for measuring thermal conductivity is Parallel plate method. This measurement technique has gained popularity because of the fact that the thermal conductivity of the liquid can be measured simple way with a good level of accuracy and repeatability. Here is introduced Modified parallel plate method, in which, the experimental procedure, calibration of experimental set up is explained. In this study, a detailed description of an modified parallel plate method developed by the present research group has been presented and prepared the experimental set up, procedure, calibration and data reduction. In this experiment the calibration of the proposed experimental set up and employs to determine the thermal conductivity of liquids.The results are promising for thermal engineering applications.

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