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Study of Measurement of Liquid Thermal Conductivity Using Modified Perforated Guarded Hot Plate Apparatus

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Abstract:
The thermal conductivity of liquids plays a crucial role in various engineering and scientific applications, such as heat transfer analysis, fluid flow modeling, and energy systems design. While the measurement of thermal conductivity in solids is well-established, assessing liquid thermal conductivity is intricate due to convective heat transfer and molecular complexity. Accurate measurement of liquid thermal conductivity is essential for understanding and optimizing thermal performance in these applications. The Hot Wire Method, Modified Hot Wire Method and Radial Heat Conduction Apparatus are widely used techniques for determining the thermal conductivity of liquids. But for first two methods, costs of apparatus are very large and remaining method is less accurate. This paper introduces a novel modified guarded hot plate apparatus designed for precise liquid thermal conductivity measurement. The guarded hot plate apparatus is generally used for solid powder thermal conductivity measurement. But the modified apparatus addresses the challenges of convection-induced errors in liquid by employing a thin liquid layer, strategic temperature field setup, and a perforated acrylic sheet to curtail fluid motion. The study discusses heat transfer mechanisms, mathematical models for calculating thermal conductivity, and error reduction considerations. This modified apparatus is developed and its accuracy and validity is confirmed with readings of distilled water. The study extends to the characterization of ethanol's thermal conductivity, showcasing the apparatus's applicability. A derived mathematical equation further predicts thermal conductivity of ethanol within a specific temperature range (25 to 55^{o}C). Results obtained from experiments indicate that modified apparatus measure thermal conductivity of liquid with small error of 0.5% to 3%. This contribution provides affirmative solution for liquid thermal conductivity measurements in smaller range of temperature with smaller apparatus cost.
***Key Word**:Thermal Conductivity of Liquid, Modified Guarded Hot Plate Apparatus, Perforated Plate*

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I. Introduction

The characterization of thermal properties is essential for understanding the behavior of liquids in various heat transfer processes. Thermal conductivity, in particular, quantifies a material's ability to conduct heat and is a fundamental property required for accurate thermal analysis. While the thermal conductivity of solids is well-studied and characterized, the measurement of liquid thermal conductivity faces unique challenges due to the inherent fluidity, convection dominant mode of heat transfer and molecular complexity of liquids.

There are number of ways to measure thermal conductivity of materials. Each of these is suitable for a limited range of materials, depending on thermal properties and the temperature. There is a distinction between steady state and transient techniques.

In general, steady state techniques are useful when the temperature of the material does not change with time. The transient techniques perform a measurement during the process of heating up. Possible methods of measurement of thermal conductivity of liquids are [9]

a) Hot Wire Method
b) Modified Hot Wire Method
c) Guarded Hot Plate Apparatus
d) Radial Heat Conduction Apparatus for Liquids and Gases

First two methods are transient or unsteady state method and last two are steady state methods. The problems associated with the transient methods are mathematical analysis of data is more difficult and second, the cost of apparatus is comparatively very high. On the other hand, the problems associated with the steady methods are to avoid the heat transfer by convection and it takes comparatively more time for measurements. Transient methods require simultaneous measurements of time, density, specific heat, area, length and quantity of heat flow. On the other hand, steady state methods only require measurement of heat flow rate, temperature, area and the length[7].

The main problem connected with the measurement of liquid thermal conductivity is that necessity to make the liquid Steady. If liquid is moving, the heat transfer takes place by the convection not by conduction. In presence of temperature variation and in presence of gravity, the liquid will start moving around due to natural conviction.

Above paragraph emphases that for measurement of thermal conductivity of the liquid, it is essential to stop the convection heat transfer in the liquid completely, but it is very complicated task to design and fabricate such apparatus.

This paper aims to introduce the newly suggested modified guarded hot plate apparatus for accurate liquid thermal conductivity measurement. In modified apparatus, three ways are used to minimize the fluid particles movement due to convection in steady state situation. 1) Use of very thin layer of the fluid in the direction of temperature gradient so that the Grashoff's Number is very small and results in laminar flow. 2) Set up the temperature field in the fluid such that the hot part is above the cold part and hence the layers in the stable configuration. 3) Perforated acrylic sheet is used to place sample liquid in the guarded hot plate apparatus which will stop the convection in liquid greatly in horizontal direction.

By considering these things, modified guarded hot plate apparatus was developed. In this paper, heat transfer mechanisms involved in apparatus, mathematical models used to calculate thermal conductivity, and considerations for minimizing experimental errors are discussed.

II. Modified Guarded Hot Plate Apparatus

The guarded hot plate apparatus is generally used for thermal conductivity measurement of Powder materials. In the present work, this apparatus is modified to measure thermal conductivity of liquids. The principle of the modified guarded hot plate method is to generate a known unidirectional heat flux through the testing liquid placed in perforated plate so that they appear as slabs of infinite width bounded by parallel planes with minimum convection. To achieve these aims, it is customary to use a heater plate comprising two parts, a central main heater plate (or metering area plate or main heater) surrounded by an annular guard plate. These plates are separated from each other by a small air gap, which acts as a thermal barrier. It is shown in fig. 1. Heat flows from the metering area of the main heater plate through the specimens to cold plate maintained at a stable lower temperature. The gap between main heater plate and cold plate is very small around 1 to 1.5 mm to get laminar flow in gap. In the cold plate, water jacket is provided to maintain constant low temperature. Electrical current is supplied to main heater independently of the metering area which generates the heat flux. Under steady state heat transfer, isothermal planes across the measured region of the specimen are developed.

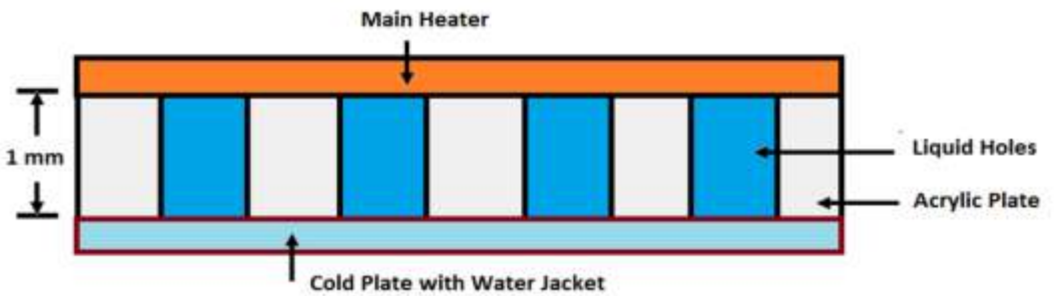

Figure 1: Modified guarded hot plate apparatus

To avoid the heat loss and convection in horizontal direction, another heater is provided in annular guard plate as shown in fig. 1. This heater maintains the same temperature as that of main plate temperature with the help of separate dimmer stat. Hence there is no temperature difference in horizontal direction and hence minimum heat transfer in that direction by conduction as well as convection through testing liquid which is required in thermal conductivity measurement.

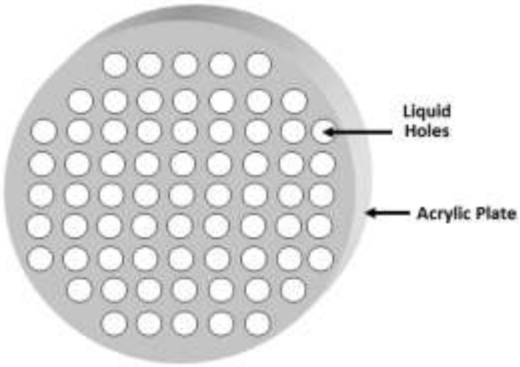

Figure 2: Perforated acrylic plate to place the liquid sample

In addition to this, perforated acrylic plate is used having 10cm diameter and 1mm height. Acrylic plate has 52 holes of 7mm diameter to fill the sample liquid into them. The perforated plate is shown in fig. 2. Small diameter holes allow only heat transfer by conduction through liquid and it will stop the convection by greater percentage. Therefore these modifications in apparatus help to measure liquid thermal conductivity with high accuracy. It is verified in this paper.

III. Experimental Setup and Investigation

The construction of a modified guarded hot plate apparatus for liquid thermal conductivity measurement involves several key components and considerations. Here is a general outline of the construction process.

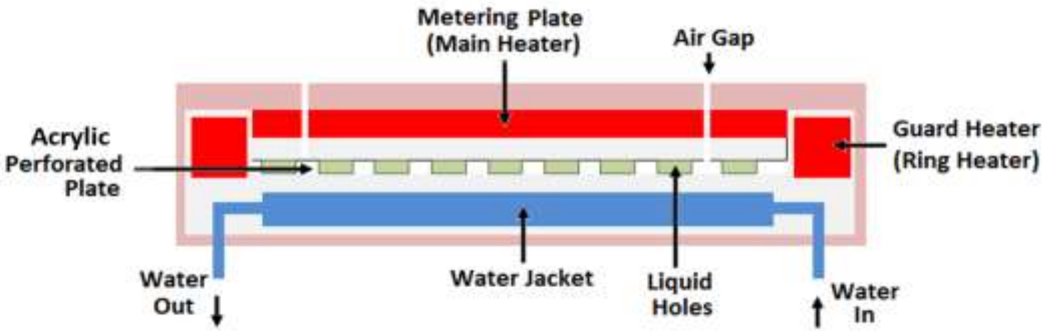

Figure 3: Position of main heater and guarded heater in the apparatus

It consists of base plate that serves as the foundation for the device. In the apparatus, two heating plates are provided. The metering plate will serve as the main heating element, while the outer plate acts as a guard to minimize heat losses. Two thermocouples on the inner plate and two thermocouples on outer plates are provided to measure the temperatures at specific locations. Positions of thermocouples are in close proximity to the liquid sample, ensuring they make good thermal contact with the plates. In addition to these, two more thermocouples are provided for inlet and outlet temperature of water in cold plate. 100 W electric heater is incorporated in main plate and 150 Micathermic electric heater is used as guarded heater in outer plate. Expanded polyethylene foam is used as insulating material in the apparatus to minimize heat loss to the surroundings. Apparatus is incorporated with glass and reflective coatings to minimize convection or radiation to surrounding. Control Panel is provided with dimmerstat, voltmeter, ammeter, digital temperature display and rotameter. Experimental Set up is shown in Fig. 3 and 4. The validity of the experiment set up is checked with distilled water. Experimental work is carried out to determine thermal conductivity of Ethanol.

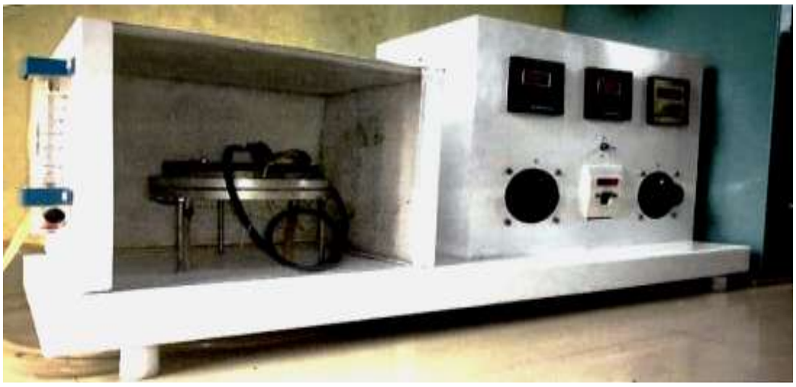

Figure 4: Photograph of guarded hot plate apparatus

During experiment, sample liquid is filled properly in holes of perforated acrylic plate placed in the metering region of main heating plate. Then voltage is applied to main heater to get required temperature at which thermal conductivity has to measure. The cooling water is circulated through water jacket of cold plate. After 15 minutes, the electrical energy is supplied to guarded heater such that the temperature of main plate and guarded plate are maintained same throughout experiment. Temperatures (T1 to T6) are measured after every 5 minute till steady state condition is reached. Readings are taken for different temperatures and calculations are done to determine thermal conductivity of liquid.

IV. Thermal Analysis of Guarded Hot Plate Apparatus

The calculations involved in the modified guarded hot plate apparatus for liquid thermal conductivity measurement primarily revolve around heat transfer through acrylic plate, measured temperature data, electric energy supplied and known experimental parameters. Electrical analogy of heat transfer is used for this analysis. Here are the key calculations involved:

D_p is diameter of main heater plate = 0.1m
D_h is diameter of liquid holes in acrylic plate = 0.007m
b_h is thickness of holes in acrylic plate = 0.001 m
$(bp)_h$ is thickness of main heater plate = 0.005 m
$(bp)_c$ is thickness of cold water plate = 0.005 m
N is number of holes provided in acrylic plate= 52
K_p is thermal conductivity of main heater plate=237 W/mK
K_A is thermal conductivity of acrylic material = 0.2 W/mK
Heat supplied by main heater to the plate in watt is given by

$$Q = V \times I$$

Where, 'V' is voltage applied and 'I' is current flowing through heater
Area of the plate attached to main heater is

$$A_p = \frac{\pi}{4} D_p^{\,2}$$

Area of single liquid hole provided in acrylic plate is calculated by

$$A_h = \frac{\pi}{4} D_h^{\,2}$$

Total area of liquid holes provided in acrylic plate is

$$A_{ht} = N \, x \, \frac{\pi}{4} D_h^{\,2}$$

Actual area of acrylic plate used in the apparatus is given by

$$A_A = A_p - A_{ht}$$

Equivalent electrical circuit diagram for guarded hot plate apparatus is shown in Fig. 5.

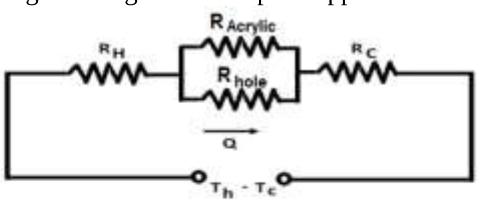

Figure 5: Equivalent electrical circuit diagram for apparatus

Thermal resistance offered by main heater Plate (R_H) is

$$R_H = \frac{(b_p)_h}{K_p A_p}$$

Thermal resistance offered by water jacket side plate (R_C) is

$$R_C = \frac{(b_p)_C}{K_p A_p}$$

Thermal resistance in the loop is calculated by

$$\frac{1}{R_{loop}} = \frac{1}{R_{hole}} + \frac{1}{R_{acrylic}}$$

Where,

R_{hole} is thermal resistance offered by the liquid in the holes to heat transfer

$$R_{hole} = \frac{b_h}{K_L A_{ht}}$$

$R_{acrylic}$ is thermal resistance offered by the acrylic plate to heat transfer

$$R_{acrylic} = \frac{b_h}{K_A A_A}$$

Equation obtained from electric analogy is

$$Q = \frac{\Delta T}{R_{th}}$$

Where R_{th} is total resistance offered by the system

$$R_{th} = R_H + R_{loop} + R_C$$

Therefore, we get

$$Q = \frac{T_h - T_C}{\frac{(b_p)_h}{K_p A_p} + \frac{b_h}{K_L A_{ht} + K_A A_A} + \frac{(b_p)_C}{K_p A_p}}$$

Where T_h is temperature of main hot plate and T_c is temperature of cold plate
Solve above equation for unknown thermal conductivity of the liquid i.e. K_L

$$K_L = \frac{1}{A_{ht}}\left[\left(\frac{b_h}{\left(\frac{T_h - T_C}{Q} - \frac{(b_p)_h}{K_p A_p} - \frac{(b_p)_C}{K_p A_p}\right)}\right) - K_A A_A\right]$$

V. Result Discussion

The validity and accuracy of the experimental setup is checked before it is used to measure thermal conductivity of any given liquid. It is done with the distilled water. Thermal conductivity of distilled water is measured with developed modified guarded hot plate apparatus for different range of temperatures. The experiments are conducted for temperature range from 25 ^{o}C to 55 ^{o}C. Readings are taken and calculations are performed by using above mathematical model. The calculated thermal conductivities are compared with actual thermal conductivity of distilled water and thermal conductivity obtained from simple guarded hot plate apparatus i.e. without perforated plate. The results are summarized in the form of Fig 6.

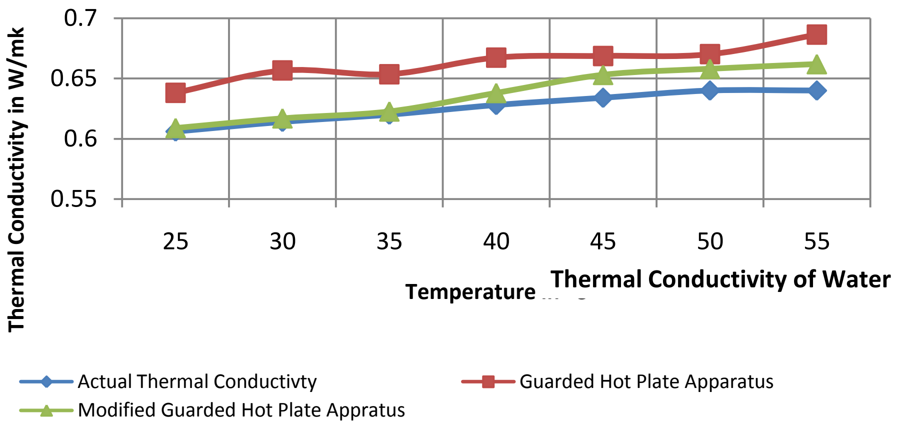

Figure 6: Thermal conductivity of the distilled water at different temperatures

The graph shows that there is 4.70% to 7.25 % error in thermal conductivity measured with simple guarded hot plate apparatus as compare to the actual thermal conductivity of distilled water. On the other hand, it is observed that error in thermal conductivity measurement is very less around 0.43% to 3.42 % when modified guarded hot plate apparatus is used. Hence it can be said that the developed modified apparatus is valid to measure the thermal conductivity of any given liquid with considerable accuracy. But it is also observed that percentage of error increases with increase in temperature. Hence apparatus is valid in smaller range of temperature.

Measurement of Thermal Conductivity of Ethanol

Experimental work is carried on Ethanol to determine its thermal conductivity for temperature range 25 ^{o}C to 55 ^{o}C. The results are plotted in the Fig 7. It shows that thermal conductivity of Ethanol decreases with increases in temperature. For all liquids, thermal conductivity is always inversely proportional to its temperature. Same observation is verified by the obtained results.

The results are also used to generate the mathematical equation for thermal conductivity of Ethanol as function of temperature.

$$K(T) = 0.1973 - 0.0425\,T + 0.017083333\,T^2 - 0.002083333\,T^3$$

The above equation is developed by using Newton's divided difference interpolation formula. It predicts the thermal conductivity of the Ethanol for temperature range 25 to 55 ^{o}C with deviation of 1% to 1.5 % as compared to actual measured values.

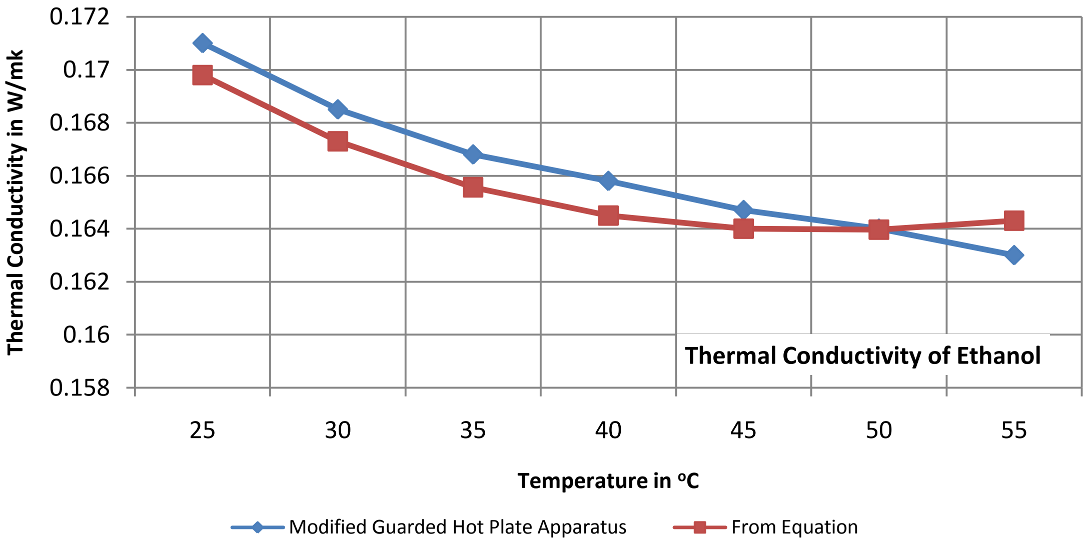

Figure 7: Thermal conductivity of the Ethanol at different temperatures

VI. Conclusion

In conclusion, this paper presents a novel and practical solution to address the challenges associated with precise measurement of liquid thermal conductivity. Traditionally, guarded hot plate apparatus is used for solid powder thermal conductivity measurements, but proposed modified apparatus overcomes the complexities of liquid measurements by incorporating several key elements such as utilizing a thin fluid layer, strategically designed of hot and cold temperature fields, and a perforated acrylic sheet to minimize fluid motion. The modified guarded hot plate apparatus successfully mitigates the effects of convective heat transfer. The study thoroughly discusses the underlying heat transfer mechanisms and presents mathematical models for calculating thermal conductivity, taking into account the specific conditions of the modified setup.

The developed accuracy and validity of apparatus are confirmed through experimental readings of distilled water. Furthermore, the applicability of the apparatus is extended to measure of ethanol's thermal conductivity, showcasing its versatility and potential across different liquids. The experimental results obtained from the conducted tests on distilled water and ethanol exhibit remarkable precision, with errors ranging from only 0.5% to 3%. A derived mathematical equation enhances the practical utility of the apparatus by enabling the prediction of ethanol's thermal conductivity within a specific small temperature range. This outcome underscores the successful implementation of the modified apparatus in addressing the inherent challenges of liquid thermal conductivity measurement with a significantly reduced cost compared to existing methods.

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