Assessment of Thermal Conductivity of Liquids by Modified Parallel Plate Method

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***Abstract* — Concept and purpose of this paper was to develop a method to measure thermal conductivity of liquids and explain theoretical basis. In this method uses modified parallel plate thermal conductivity apparatus and compare the measured thermal conductivity of engine oil and radiator coolant from apparatus to the reference value of these liquid from data book. Most of the researchers have been try to find the best method to improve heat transfer rate, increase the thermal conductivity of the liquids. Heat transfer plays a main role in most of the fields like power generating plants, transportation, microelectronics and air conditioning because the heating and cooling processes involved. To increase the efficiency, in the above field's uses heat transfer devices, of such an improvement, it becomes possible to reduce the size of the devices. Other major parameters in heat transfer are the thermal conductivity of the working liquid used in the system. Applications of the liquids in the thermal systems have been well documented in the researcher and industrial groups. Modified Parallel Plate Thermal Conductivity (MPPTC) apparatus is developed to measure the thermal conductivity of liquids. This apparatus consists of heater assembly above the test liquid specimen and a chiller assembly below the test liquid specimen. This apparatus creates a difference in temperature which is measured by calibrated thermocouples which is placed in the parallel plates. This temperature difference can be used, with the heating power, to calculate the thermal conductivity of the test liquid specimen. This concept, with a sufficiently minimum thickness of test liquid layer, prohibits convection effect in the test liquid specimen and creates a heat transfer mechanism because of conduction mode. This apparatus is fully insulated for restricting nearly all heat conduction to the all direction. This MPPTC apparatus has been calibrated to ensure accurate and precise measurement results. All thermocouples are calibrated and incidental heat loss has been calculated to minimize errors occurring in liquid thermal conductivity measurements due to heat loss through the apparatus. Distilled water has been used in MPPTC apparatus to calculate incidental heat loss. Engine oil and radiator coolants have been used in MPPTC apparatus to measure thermal conductivity which produces accuracy of approximately 95 % confidence.**

Keywords—Modified Parallel plate method, engine oil,radiator coolant, thermal conductivity, experimental procedure, calibration.

I. INTRODUCTION

Thermal conductivity values are very much essential whenever a heat transfer problem is to be evaluated. There are many methods available for measuring the thermal conductivity of liquids but all of them require purchasing or building new equipment. The purpose of this work is to develop and verify a new method, which can be used at laboratories. Heat always transfers from a higher temperature region to a lower temperature region. In nature there are three mechanisms of heat transfer; it can be transferred together with all the mechanisms, with only two of them or with only one mechanism. Conduction, Convection and Thermal Radiation are three modes of heat transfer mechanism. Thermal conduction is significant topic in the study of heat transfer. Conduction is the transfer of energy from energetic particles to the adjacent less energetic of a substance, as a result of interactions between these particles. Conduction takes place in solids, liquids, or gases. Gases and liquids, conduction is due to the collision and diffusion of the molecules during their random motion (1).

II. THERMAL CONDUCTIVITY MEASUREMENT THEORY

To fully understand how the steady-state, Modified Parallel-Plate Thermal Conductivity (MPPTC) Apparatus functions, it is important to first understand the physical phenomena governing the apparatus. This analysis starts with one dimensional heat transfer is done by the Fourier's Law of thermal conduction.

$$Q_X = -KA\,\frac{dT}{dx} \qquad (1)$$

This equation states that, for homogeneous media, the heat transfer rate between two points in the x-direction shown in figure 1 is equal to the product of the thermal conductivity of the wall (k), the cross-sectional area of the media (A), and the negative local temperature gradient in the x-direction $(-\frac{dT}{dx})$.This equation can be rearranged to obtain Equation 2

$$Q_X \times dx = -KA\,dT \qquad (2)$$

This equation is then integrated over the plane wall illustrated in Figure 1 (assuming k constant). The resulting equation is Equation 3.

$$Q_X = -KA\,\frac{(T_1 - T_2)}{L} \qquad (3)$$

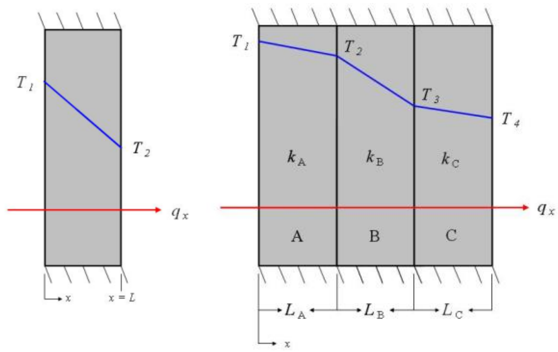

Figure 1: Plane and Composite Wall Heat Conduction

Equation 3 can be applied to the composite wall shown in Figure 1. This yields Equation 4

$$Q_X = \frac{T_1 - T_4}{\frac{L_A}{K_A A} + \frac{L_B}{K_B A} + \frac{L_C}{K_C A}} \quad (4)$$

The composite wall is made up of three plane walls, A, B, and C. These three plane walls have thermal conductivities k_A, k_B, and k_C, and thicknesses L_A, L_B, and L_C. Because the heat conduction through a stationary liquid is identical to the heat conduction through a solid medium, this concept can be applied to obtain the steady-state, Modified parallel-plate method of determining liquid thermal conductivity. Modified parallel plate methods (steady state) utilize the mathematical model of heat transfer through composite wall, Equation 4 used to determine the thermal conductivity of liquid. In Figure 1, the parallel plates are represented by walls A and C. The fluid of unknown thermal conductivity is represented by wall B. The heat transfer rate in the x-direction means q_x is a measured value. This is practical because q_x is simply the amount of heat rate provided to one side of the parallel plates, and is usually provided by a known heating power source. Next, the physical dimensions such as the various lengths, L_A, L_B, and L_C, and the cross-sectional area, A, are also known, measured values. In practice, these dimensions are specifically designed to optimize the accuracy, precision, and efficiency of the PPTC Apparatus. Parallel plates, represented in Figure 2 by A and C are made of a material with a known value of thermal conductivity. Therefore, k_A and k_C are known, constant values. The temperatures T_1 and T_4 are also measured. In practice, these two temperatures are usually measured using either thermocouples or RTDs. This leaves k_B as the only unknown quantity. Equation 4 can be solved for k_B, yielding Equation 5. The term k_B represents the unknown thermal conductivity of the test liquid specimen.

$$K_B = \frac{L_B}{A\left[\frac{T_1 - T_4}{Q_X} - \frac{L_A}{K_A A} - \frac{L_C}{K_C A}\right]} \quad (5)$$

III. DEVELOPMENT OF MODIFIED PARALLEL-PLATE THERMAL CONDUCTIVITY (MPPTC) APPARATUS

Present paper explains modified parallel plate experimental set up to determine the thermal conductivity of liquids. Present paper used guarded hot plate method instead of guard heater replaced by whole assembly with good insulator (glass wool). A good arrangement (experimental set up) and experiment procedure is found from experimental set up and procedure in the literatures review explained [2-4].

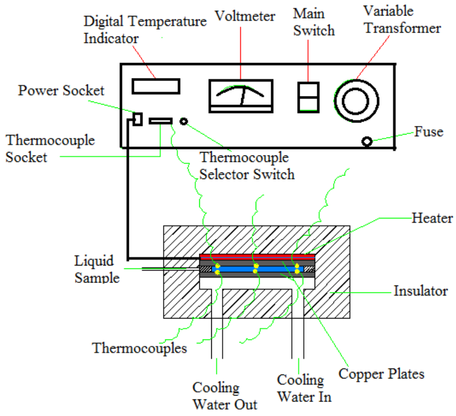

Figure.2 Outline of experimental Set Up.

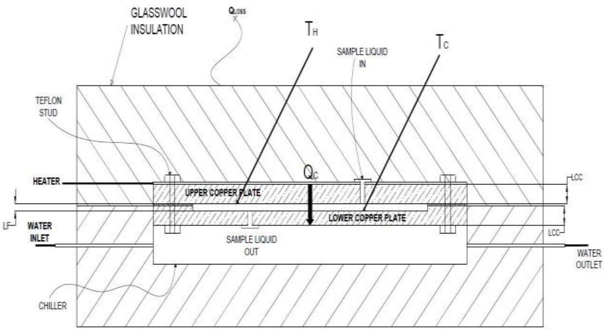

Figure 3: Schematic of MPPTC apparatus

The schematic of MPPTC apparatus with all components labeled and related nomenclature is presented in Fig.3.To provide controlled one-dimensional heating by conduction through a stationary test liquid specimen and measurements of the temperatures for accurate measurement of the liquid thermal conductivity [6-9].

A. Test liquid specimen cavity

This is critical component of this apparatus which houses the test liquid sample to measure thermal conductivity. The test liquid cavity are developed by Teflon sheet of 0.1mm whose low thermal conductivity of 0.35 *W/m-K* it provides insulation to the copper parallel plates, so it will restrict direct contact of the parallel plates, top side of lower copper plate a groove of diameter 150 mm which is of 0.3 mm deep is provided. So the thickness of the test liquid specimen cavity becomes L_F = 0.4 mm. The faces of the parallel plates in contact with the test fluid specimen have a high level of planarity and mirror-polished finish which is done by lapping process to minimize measurement errors due to surface geometry imperfections of the parallel plates. The test fluid specimen cavity is placed between the upper and lower copper plates with the help of Teflon stud and bolt. To measure the thermal conductivity of the sample liquid specimen, a well-defined heat transfer mechanism consisting conduction is provided. This is accomplished by two major design parameters, first the Heater is above and the Chiller assembly is below the test liquid (the heat transfer is in the gravity direction) thus convection effects due to buoyancy. The second major design parameter is a very small thickness of the test liquid specimen cavity, L_F =0.4 mm. This prevents the convection from developing within the test liquid specimen.

B. Parallel Copper plates

The parallel plates provide the plane surfaces that comprise the top and bottom of the test liquid specimen cavity. Thermocouples are provided in copper plates which are used to measure a number of temperatures at different locations and also used to determine the temperature difference across the test liquid specimen, as well as temperature uniformity in the other two directions, see Fig.3. The parallel plates are made from copper of thickness of 8mm. (200mm diameter).Copper material is used for the parallel plates. One surface of each of the copper plates facing the test specimen has a mirror finish. Each faces of the parallel plates facing away from the test liquid specimen have thermocouple grooves. These grooves provide locations which are needed to place thermocouples and clearance for thermocouple wires. There are four thermocouple grooves spaced uniformly around the circumference of each parallel plate. These grooves extend from the centre to the outside edge of the parallel plates and are 7mm deep and 2 mm wide. *K-type* thermocouples mounted on each parallel plate. The thermocouple grooves are then filled with a high thermal conductivity epoxy material isolates and holds the thermocouples in place. Having a large number of uniformly spaced thermocouples provides means to verify the temperature uniformity, which is needed for evaluation of heat looses, if any and validation of one-dimensional heat transfer through the thickness of the test liquid specimen, as per modeled by the working equation used for evaluation of the thermal conductivity. In Figure.3, the glass wool insulation is around the whole assembly is provided to prevent heat losses from the top side of the apparatus is also presented. The insulation is located above the heater assembly.

C. Heater design

The Heater generates the heat flux and thus the temperature difference across the test liquid specimen. The Heater is made up of a resistance wire which is formed into a spiral and sandwiched between mica sheets. Heat generated by the heater wire will be uniformly distributed across the complete surface of the test liquid specimen. The top copper plate is 8mm thickness of circular disc with 200 mm diameter. The Heater is placed at above the top copper plate and the heater is screwed together creating a single heater assembly, which creates the upper assembly of the apparatus. Teflon stud is used for the heater assembly housing for three reasons. First, the Teflon stud provides sufficient rigidity for the press fitting of the Heater assembly. Second, the low thermal conductivity of Teflon provides insulation, which reduces the amount of heat lost to the surroundings. Finally, the Teflon provides, easy cleaning of the apparatus. Upper assembly is covered with glass wool. This insulation provides around the whole assembly. The glass wool has an highly, low thermal conductivity of 0.027 *W/m-K* and hence minimizes the heat loss to the surrounding.

D. Chiller

The lower assembly of the apparatus is chiller and it utilizes cold water as its cooling agent, see Fig.3.Channel made from Bakelite sheet is designed to guide the cooling water around the lower assembly and it also provides removal of the heat generated by the Heater. The basic shape of the fluid channel is like zigzag, with the water entering the Chiller at the one corner and leaving at the other corner, which enables more uniform circumferential temperature. The fluid channel has an outer circumference of 200 X 200 mm and a depth of 25 mm. The channel walls are 5mm thick, which provides sufficient rigidity. The Chiller is also comprised of a copper plate that forms the top of the Chiller assembly and provides even heat transfer to the Chiller fluid. The material and dimensions of the Chiller copper plate are similar to those of the upper Heater copper plate.

The various components discussed above are assembled, so as to prepare experimental set up. Four thermocouples are mounted on side of copper plates. The two copper plates in between thin layer of liquid sample means test fluid cavity is placed, who's thermal conductivity is to be measured. The heater is placed on upper side of the copper plate. Cooling arrangement means chiller 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 the whole assembly the glass wool insulator is provided.

IV. TESTING PROCEDURE

MPPTC apparatus with all components labeled and relevant nomenclatures are presented in Fig 3. The objective is to provide one-dimensional heating by conduction through a stationary test liquid specimen. This assembly ensures a simple one dimensional heat conduction through parallel sections.

With the assumption of one dimensional flow the following can be utilized to calculate the liquid thermal conductivity.

$$K_F = \frac{L_F}{A\left[\frac{T_H - T_C}{Q_C} - \frac{2L_C}{K_C A}\right]} \quad (6)$$

A = Surface area (sq-m) (in this case same as cross sectional area)

L_F = Test fluid specimen thickness between two plates (m)

L_C= Thickness of copper plates (m)

K_C= Thermal conductivity of copper plates (*W/m-K*)

$$Q_C = Q_g - Q_i \quad (7)$$

Typically in MPPTC apparatus the Q_g is calculated by

$$Q_g = V \times I \quad (8)$$

Where Q_i is the incidental heat loss through the apparatus. The V_{heater} and I_{heater} are measured voltage and current across and the Heater. The T_H and T_C are representative temperatures at upper and lower parallel copper plates.

To check the validity of the apparatus, calibration test is done with the help distilled water as a test fluid. The data from the distilled water calibration test is used to calculate Q_C from, using the known thermal conductivity of distilled water, k_{water}. Value for Q_g is then calculated, to get q_{loss}. The graph of the Q_i (q_{loss}) vs. Average temperature values is the calibration curve. The data from test carried on the distilled water calibration test is used to calculate Q_C from Equation 7, using thermal conductivity of distilled water. The value for Q_g is then calculated and Equation 8 solved for q_{loss}. The graph of the Q_i (q_{loss}) vs. Average temperature values signifies the calibration curve.

Procedure for calculation of incidental heat loss (distilled water).

1. Connect the small flexible tubes to the charging of sample to the provision provided at the end of the hot copper plate and cold copper plate to close off the chamber. After, distilled water is introduced in the gap between parallel plates.

2. Switch on electrical supply.

3. Adjust the variable transformer up to 10 V.

4. Observe the hot and cold copper plate temperatures and when they are steady, note down their values and the current and voltage in the observation Table.

5. Increase the electrical input up to 20 V and the temperature of copper plates is stable repeat the step above.

6. Repeat again for 30 V, 40 V, 50 V, 60 V, 70 V, 80 V, 90 V, 100 V.

7. Calculate the incidental heat loss and then plot the heat loss as a function of the average temperature. This will be incidental heat loss curve for the testing of other liquids like engine oil and coolants. Now precede as per procedure explained using voltages 10 to 100 V. Calculated thermal conductivity values comparing with reference values of (k) for engine oil, use at the mean temperatures from data book.

V. RESULTS AND DISCUSSION

A. Incidental heat loss(Calibration curve)

Table 1: Incidental heat loss from apparatus using distilled water

Sr. no.	TH	TC	dt =TH-TC	Tavg.	Thermal conductivity(K) From Data Book	Voltage (V)	Current (I)	Qg	Qc	Qi
1	33.5	33.25	0.25	33.38	0.620	10	0.974	9.74475	6.40828	3.33647
2	34.75	34.25	0.5	34.50	0.620	20	1.176	23.5108	12.8166	10.6943
3	35.5	34.5	1	34.63	0.620	30	1.224	36.7177	25.6331	11.0846
4	37	35.25	1.75	36.00	0.628	40	1.519	60.7794	45.4014	15.378
5	37.75	35.75	2	36.63	0.628	50	1.384	69.2169	51.8873	17.3296
6	39.25	36.75	2.5	37.88	0.628	60	1.435	86.0918	64.8591	21.2327
7	40	37	3	38.38	0.628	70	1.437	100.625	77.8309	22.7939
8	42.5	39	3.5	40.75	0.634	80	1.523	121.827	91.6168	30.2099
9	46.25	41.75	4.5	44.13	0.640	100	1.596	159.587	118.838	40.7483
10	52.75	47.75	5	50.25	0.645	110	1.753	192.883	133.01	59.8736

The values of Q_i , it means Q_{loss} for the engine oil and radiator coolants used for measuring thermal conductivity (it is assumed that heat loss is directly related to average temperature). The Q_{loss} from the graph and the calculated value of Q_g for the engine oil and coolants tests are then put into Equation 7 to calculate Q_C. The value of Q_C put into equation 6 got the experimental thermal conductivity of engine oil and radiator coolants.

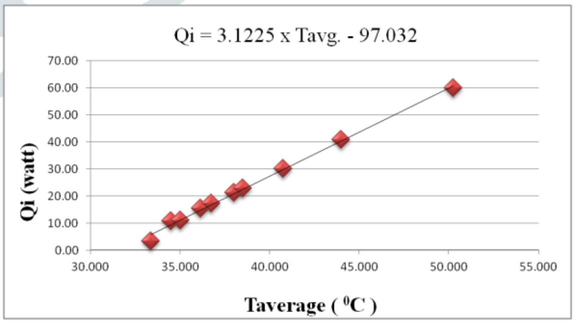

Figure 4: Graph shows the incidental heat loss vs temperature average.

B. Engine oil

After experimentation the results are provided in result tables.

Table 2: Comparisons of engine oil between experimental values vs. values of data hand book [13]

Sr.no.	Tavg.	Thermal conductivity (K) W/mK	Thermal Conductivity (K) from data hand book W/mK
1	35.25	0.139	0.145
2	35.63	0.139	0.145
3	36.00	0.138	0.145
4	38.13	0.138	0.145
5	40.13	0.136	0.143
6	41.63	0.136	0.143
7	45.63	0.136	0.143
8	49.13	0.134	0.141

Graphs are plotted to results found from above system, graphical representation is important for understanding the system behavior for various input parameters. Graph represents thermal conductivity of engine oil calculated from MPPTC apparatus verses thermal conductivity from data book.

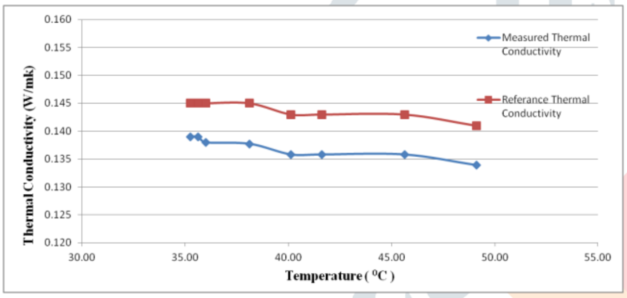

Figure 5: Experimental Values vs. Data book values of engine oil

Figure 5 shows graph between thermal conductivity of engine oil calculated from MPPTC apparatus verses thermal conductivity from data book at different heat inputs and temperatures. The figure 5 show as engine oil temperature increases, its thermal conductivity decreases. Graph shows values of experimental are close to the exact values taken from data hand book with a minor deviation of 5%.

C. Radiator coolant

After experimentation the results are provided in result tables. Results are calculated in result tables, the graph shows results calculated from above system.

Table 3: Comparisons of radiator coolants between experimental values vs. values of data hand book [13]

Sr.no.	Tavg.	Thermal conductivity (K) W/mK	Thermal Conductivity (K) from data hand book W/mK
1	35.63	0.114	0.125
2	36.25	0.120	0.125
3	37.00	0.121	0.125
4	37.25	0.121	0.125
5	40.25	0.123	0.126
6	41.75	0.124	0.126
7	44.38	0.125	0.126
8	45.38	0.125	0.126

Graphical representation of the system behavior for different input parameters, the graph represents thermal conductivity of radiator coolants calculated from MPPTC apparatus verses thermal conductivity from data hand book.

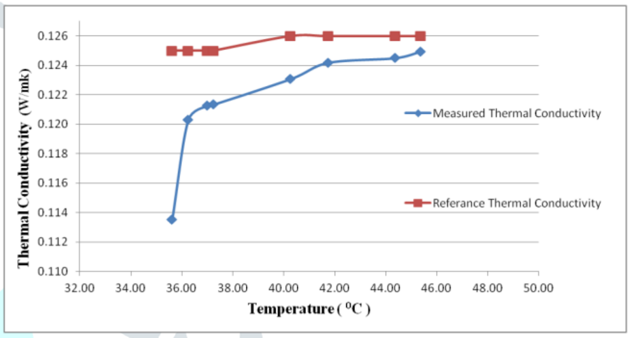

Figure 6: Experimental values vs. data hand book values of radiator coolants

Figure 6 shows graph between thermal conductivity of radiator coolants calculated from MPPTC apparatus verses thermal conductivity from data hand book at different heat inputs and temperatures. Figure 6 shows as coolant temperature increases, its thermal conductivity also increases. Graph shows the experimental values very close to the exact values of data hand book with a minor deviation of 5 %.

VI. CONCLUSION

The performance of modified parallel plate thermal conductivity apparatus with the use of engine oil, radiator coolants has been investigated in the present work. The thermal conductivity of these liquids has been observed. The measurement setup was developed and was optimized with a numerical simulation. The goal of the study was to validate the method by comparing measurement results to the reference values for used liquids from data book and to improve the method so the difference in those values would be minimal.

During the first measurements, the setup showed significant errors, when comparing the results to the reference values. We studied and measured the incidental heat loss from the modified parallel plate thermal conductivity apparatus. Further investigation showed a great impact of the difference in thermal conductivity between the measured and the reference liquid. This means that a calibration curve is found with equation to fit the chart. Therefore, the effect of this chart is useful to calculate the heat losses at various temperatures, when compared to a liquid of different thermal conductivity. To reduce this error, liquids of similar thermal conductivity should be used. Due to the lack of time, measurements on higher temperatures have not been properly investigated. The MPPTC method for measuring the thermal conductivity of liquids can be easily used every temperature laboratory, without acquiring any additional equipment.

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