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Development of the Apparatus to Measure the Thermal Conductivity of Liquids

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Abstract

An apparatus is designed and fabricated to measure the effective thermal conductivity of liquids under various temperature ranges. The uniform heat flux has been applied radially inward by placing heating element at the outer surface of the test cylinder circumferentially. Natural convection heat transfer has been experimentally investigated to find out the heat loss to atmosphere. The apparatus is completely different form of thermal conductivity apparatus which has been widely applied in normal laboratory. Uniform cooling of water is carried out by natural convection to air. The temperature distribution along the radial distance with respect to the time was recorded.The thermal conductivities of distilled water were measured using the system and the results obtained were compared with the standard values. The results obtained certified the aim of the work which was to develop the thermal conductivity measurement apparatus suitable for data collection and experimental experience in economic way.

Key words: *Thermal conductivity, water, Natural convection, radially inward flow, vertical cylinder, Heat transfer coefficient.*

1. Introduction

The thermal conductivity of liquids is one of the most important transport properties in heat transfer through fluids. In fact, it is a property of fundamental interest in developing the theory of fluids. Accurate measurements of thermal conductivity are of considerable difficulty. Methods and geometries abound each with its adherents and its inherent drawbacks. There are a number of presently existing methods to measure thermal conductivity of liquids. Each of these is suitable for a limited range of materials, depending on the thermal properties and the medium temperature. In steady-state techniques, the radial heat flow method has proven to be very successful in measurements of thermal conductivity. In radial system, heat flows radially away from a heater towards a heat sink, and thermal conductivity can be calculated from the temperature gradient inside the apparatus. In all cases the apparatus consists of an electrically heated wire or cylinder placed at the central axis inside a hollow cylinder. The cylinder is filled with test sample and is typically liquid cooled. When steady state is reached, by using standard formulae and thermocouple records, thermal conductivity can be calculated. Maglic*et al.* [1] used radial flow method with different position of thermocouple to measure the thermo physical properties. Maglic*et al.* [2] also worked with various measurement techniques i.e. Guarded hot plate method, Axial Heat Flow and Cylindrical method. The natural convection heat transfer through vertical cylinders in various configurations has been studied [3]. The natural convection heat transfer from vertical slender cylinder was investigated numerically and experimentally by many researchers. The steady state natural convection from a single cylinder with constant heat flux was studied numerically [4-6] in which limited experiments were performed. Abrahamsen *et al.*[7] tried a radial heat transfer rig that was designed for thermal conductivity measurements of low thermal conductivity specimens. Gauthier e*t al.*[8] also developed a radial flow apparatus by modifying Abrahamsen's apparatus. The present work will concentrate on the design, construction and testing of an apparatus for calculating thermal conductivity of liquids in economic way. Experiment is done in an open cylinder and the heat loss to air by natural convection is observed.

In this work, a cylindrical chamber is filled with test sample, distilled water in this case. Band heater is fitted on the outer periphery of the cylinder and thermocouples are fitted at their respective positions to measure the temperatures at different locations. Constant heat flux is supplied radially inward, towards the center and natural convection phenomenon is carried out to find out the heat loss to air. Natural convection phenomenon is characterized by a dimensionless combination of internal, buoyancy & viscous forces, known as Grashof number. Raleigh number is another dimensionless group which is studied with variation of Nusselt number to characterize natural convection.

2. Materials and Method

The procedures employed include the design stage, construction and testing of sample. The materials used were Ferritic Stainless Steel, thermal insulators (Asbestos rope and Plaster of Paris), heating system, and variable voltage power supply (variac), thermocouple (K-type).

2.1 Design Stage

The experimental setup consists of three parts viz; the heating unit sample holder cylinder and the cold-end point (Figure 1).

The heating unit consists of band heater with an electrically power supply system. The outer portion was fitted with thermal insulators for the purpose of controlling and conserving much of the heat generated by the heater. Heat was allowed to flow into the vertical cylinder to create a temperature gradient along the test sample. Ferritic Stainless Steel cylindrical chamber of 63.5 mm diameter was used to hold the test sample.

The cylindrical chamber was equally insulated from sides and bottom to reduce the heat loss. Four K-type thermocouples were embedded into the cylinder internally at two equal locations radially (two at the water surface to record surface temperatures and two immersed at equal height) and one was at the outer surface of the cylinder.

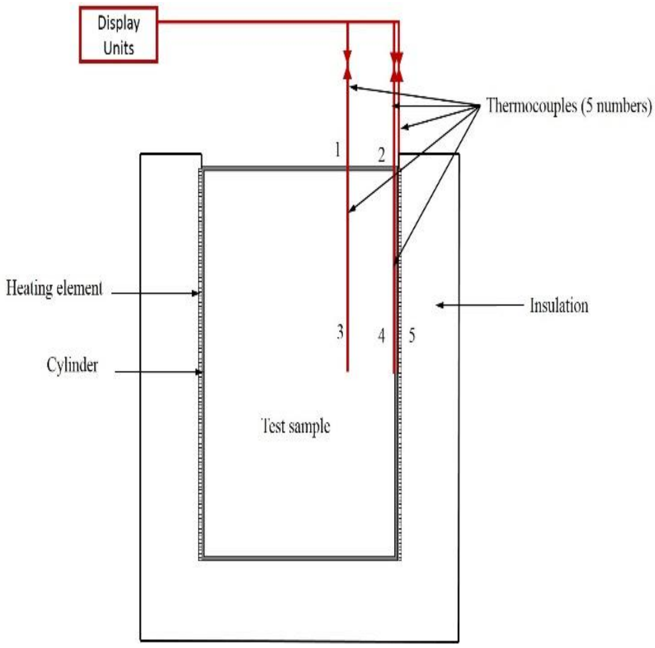
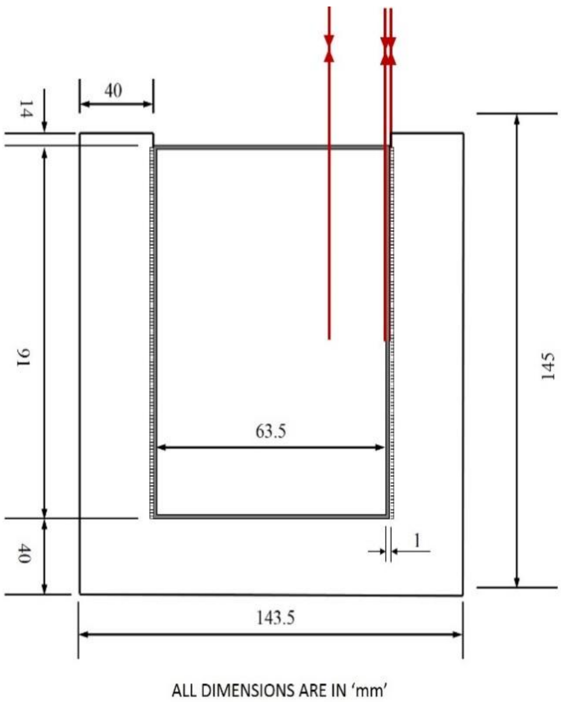


Figure:1 Schematic diagram of experimental setup. (Locations of thermocouples are shown by numeric numbers)



The cylinder was filled with distilled water heated by passing current through heater by adjusting voltage. The temperatures were seemed to be at steady state after one hour but the data was recorded for more than two hour. The temperature changes at the surface and at predetermined height of the cylinder measured by thermocouples were recorded after steady state was reached. The experiments were performed at different power inputs and corresponding data of surface & bulk temperatures of water with above procedure were recorded.

2.2 Theory

Uniform cooling of water is done by natural convection process to air from the top of the cylinder. By applying the energy balance,

$$hA_s(T_a - T_s) = \frac{2\pi L k (T_1 - T_2)}{\ln(r_2/r_1)}$$

That is, the rate at which energy is transferred to the air by convection from the water surface must equal the rate at which energy reaches the water surface by conduction from cylinder wall. That mean heat lost to air was equal to heat gained by water.

All the water properties are calculated at mean film temperature by Yunus [9]

$$T_f = \frac{T_s + T_w}{2}$$

Nusselt number

$$\overline{Nu}_L = \frac{hL}{k}$$

where h is coefficient of convection.

In case of free convection from horizontals surfaces if the characteristic length is defined as, $L = \frac{A_s}{P}$

Then for the top surface of a hot object in a colder environment or bottom surface of a cold object in a hotter environment,

$$\overline{Nu}_L = 0.54 Ra_L^{1/4} \rightarrow 10^4 \le Ra_L \le 10^7$$

The average values of surface temperature and bulk water temperature can be evaluated as:

$$\overline{T_s} = \frac{T_{s1} - T_{s2}}{\ln \frac{T_{s1}}{T_{s2}}}$$

$$\overline{T_w} = \frac{T_1 - T_2}{\ln \frac{T_1}{T_2}}$$

The Grashof, Prandle and the Raleigh numbers can be calculated as

$$Gr_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} \sim \frac{\text{buoyancy force}}{\text{viscous force}}$$

$$\overline{\Pr} = \frac{\mu C_p}{k}$$

$$Ra_L = Gr_L \Pr = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha}$$

All the physical properties (C_p, ρ, β, μ and k) of air were evaluated at average film temperature.The rate of heat transfer by free convection from the water level to the room is given by Newton’s law of cooling,

$$Q_{con} = \bar{h}A_s(T_s - T_\infty)$$

And by radiation,

$$Q_r = \varepsilon A\sigma(T_s^4 - T_{sur}^4),$$

Emissivity, ε for water was taken as 0.94 and Stefan-Boltzmann constant, σ for water was taken as 5.67 x 10^{-8}

The total heat lost from water surface to air by both convection and radiation is given by,

$$Q_T = Q_{con} + Q_r$$

And Heat transfer in case of cylindrical co-ordinate system by conduction is given by,

$$Q = \frac{2\pi L k (T_1 - T_2)}{\ln(r_2/r_1)}$$

3. Experimentation

Uniform heat was supplied to water. Temperatures were recorded for all locations. Film temperatures were calculated from above formula by considering the air temperature and average water surface temperature. Prandle numbers were calculated by considering properties of air. Grashof and the Raleigh numbers were calculated from their respective relation. Nusselt numbers were calculated from the relation between Nusselt number and Raleigh numbers. Raleigh numbers were found to be in the range in between 10^4-10^7. Coefficient of convection were calculated from the relation between Nusselt number and Coefficient of convection. After knowing the values of coefficient of convection Q_{con}were calculated and $Q_r$were calculated from the above relation. Total heat losses were calculated and from that thermal conductivity of water were calculated from the heat transfer equation for cylindrical co-ordinate. In this work, heat transfer was not calculated from the relation P = V x I, because this relation gives accurate values when heater is immersed in water i.e. in case of heat transfer radially outward.

4. Results and discussion

Radial heat transfers were validated by calculating temperature distribution in radial direction. To validate radial heat transfer in the model, the heat flux along the height of the cylinder at the different radial positions has been examined.Heat flux along the z-axis is also calculated.The result were confirmed when examining the temperature distribution in radialdirection at height z=0.0455 m, which will be the height of the thermocouples in the specimen.The theoretical temperature distribution and the actual temperature distribution have a perfect match, as shown in Figure.The theoretical values were determined by solving heat transfer equation for cylindrical co-ordinate for T_1, where the T_2 is the cold point temperature, Q is 0.7726 W and the radial position r_1 is varied.From these examinations it was safe to conclude that the 0.7726 W propagates radially in the test specimen when no heat losses were taken into account. By taking different values of heat the graph between temperature distribution vs radial position was established as shown in figure: 3.The results of this experiment were tabulated below.

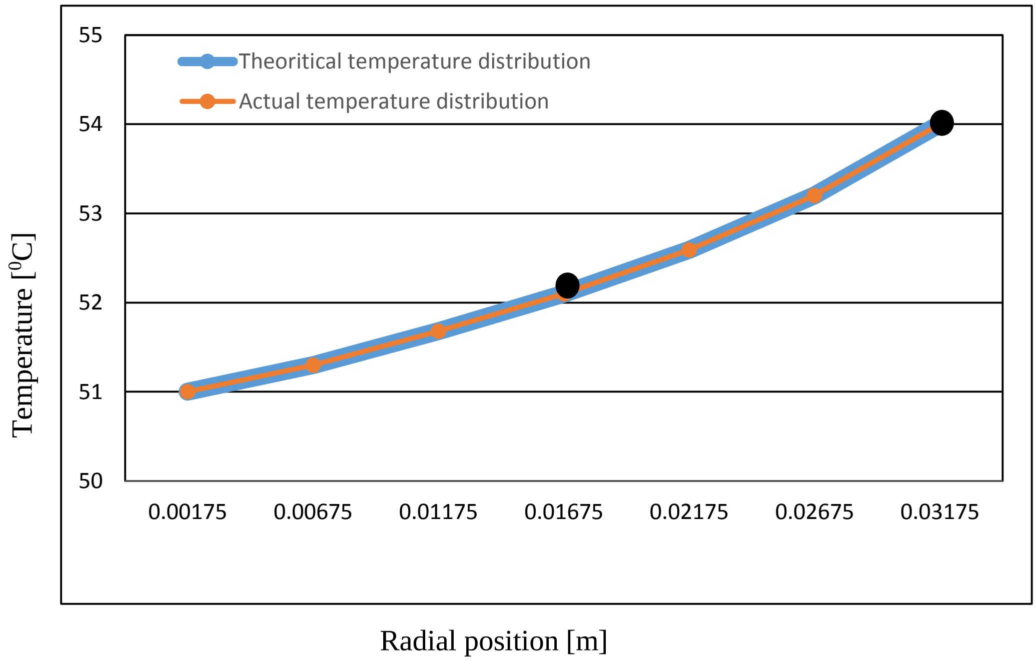


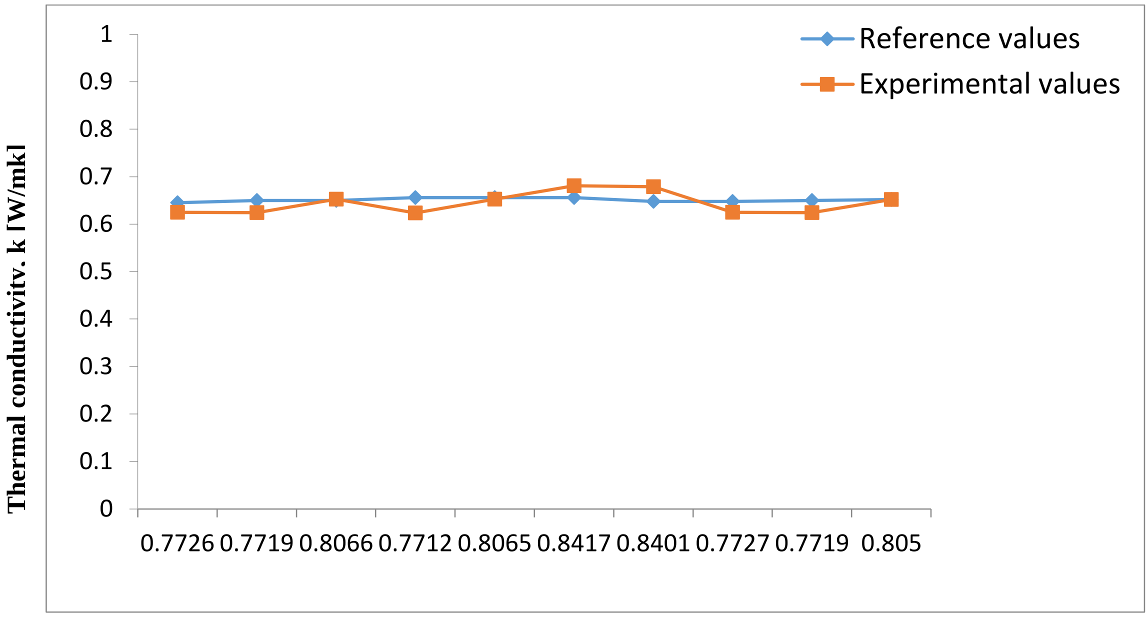
Figure: 3 Temperature distributions in radial direction for the validation of radial heat transfer. The two black circles indicates the radial locations of two thermocouples

Sl No.	Surface Temp (^{0}C)	Air Temp (^{0}C)	Pr	Gr	Ra	Nu	h	Qc	Qr	Qt	k
1	54.48	27	0.7	1.21×10^4	8.41×10^3	5.2	8.73	0.7712	1.418×10^{-3}	0.7726	0.6247
2	56.48	29	0.7	1.21×10^4	8.36×10^3	5.2	8.72	0.7703	1.6224×10^{-3}	0.7719	0.6242
3	58.48	30	0.7	1.25×10^4	8.62×10^3	5.2	8.79	0.8048	1.860×10^{-3}	0.8066	0.6523
4	57.48	30	0.7	1.20×10^4	8.33×10^3	5.2	8.71	0.7695	1.730×10^{-3}	0.7712	0.6236
5	57.48	29	0.7	1.25×10^4	7.65×10^3	5.2	8.79	0.804	1.74×10^{-3}	0.8065	0.6522
6	57.48	28	0.7	1.30×10^4	8.97×10^3	5.3	8.87	0.840	1.765×10^{-3}	0.8417	0.6810
7	60.48	31	0.7	1.28×10^4	8.89×10^3	5.2	8.85	0.838	2.130×10^{-3}	0.8401	0.6790
8	55.48	28	0.7	1.21×10^4	8.39×10^3	5.2	8.73	0.7712	1.518×10^{-3}	0.7727	0.6251
9	59.48	30	0.7	1.29×10^4	8.91×10^3	5.2	8.86	0.8397	2.005×10^{-3}	0.8417	0.6806
10	59.48	31	0.7	1.24×10^4	8.60×10^3	5.2	8.78	0.8039	1.98×10^{-3}	0.8050	0.6516

Table 1: Experimental results for distilled water

Sl. no.	Average temperature of water(^{0}C)	Thermal conductivity[10] (k)	Thermal conductivity Experimental(k)	% Error	Mean error (%)
1	54.48	0.645	0.6247	3.14	2.82
2	56.48	0.650	0.6242	3.96	
3	58.48	0.650	0.6523	0.353	
4	57.48	0.656	0.6236	4.92	
5	57.48	0.656	0.6522	0.579	
6	57.48	0.656	0.6810	3.81	
7	60.48	0.656	0.6790	3.50	
8	55.48	0.648	0.6251	3.52	
9	59.48	0.652	0.6806	4.39	
10	59.48	0.652	0.6516	0.061	

Table 2: % errors of experiments for distilled water



Heat transfer rate, Q [W]

Figure 4: Results of repeatability measurement of thermal conductivity for distilled water

5. Conclusion

The designed system for the measurement of thermal conductivity of liquid was applied to water as the test specimen. The average percentage error was 2.82% that was relatively within Standard values.

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