A Review of Different Methods of Measurement of Thermal Conductivity

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Abstract: This review paper regards with the different methods of measurements of thermal conductivity of materials. Thermal conductivity is a very important property of material. It is used in almost any thermal analysis to calculate heat transfer, exergy analysis, and many more.This reviews has been taken to get an overview over different methods of measuring thermal conductivity.

Keywords: - Thermal conductivity, temperature

1. INTRODUCTION

Thermal conductivity is the property of a material's ability to conduct heat. Its unit is watts per kelvin-meter (w/m-k)
There are various ways to measure thermal conductivity. Each of these is suitable for a limited range of materials, depending on their thermal properties and the medium temperature.
There are two major techniques to measure the thermal conductivities:

1) Steady state technique
2) Transient technique

There is a difference 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 disadvantage is that a well-designed experimental setup is needed. The transient techniques perform a measurement during the process of heating up. Their advantage is quicker measurements. Transient methods are usually carried out by needle probes.

Transient methods

1) Laser flash method
2) Transient hot wire method
3) 3ω-method
4) Transient line source method
5) Transient plane source method
6) Modified transient plane source (MTPS) method
7) Time-domain thermoreflectance method

2. FACTORSAFFECTING THERMALCONDUCTIVITY:

1. Free electrons: -

Metals are having more free electrons than liquid and gases, so metal are good conductors of heat due to movement of free electrons. Metals have closely packed lattice compared to liquids and gases.

2. Purity of material

Thermal conductivity of pure material is higher than that of alloy materials. Alloying of metals and presence of impurities cause decrease in thermal conductivity. E.g. thermal conductivity of pure copper is 385 W/mK but copper having content of arsenic, thermal conductivity is 142 W/mK

3. Effect of forming

Treatment of metals like heat treatment and metal forming like bending, drawing and forging decreases the thermal conductivity of material compared to material before treatment because at high temperature, thermal conductivity decreases.

4. High temperature

At high temperature lattice vibration increases and free electrons movement decreases due to collision, thus thermal conductivity of metal decreases when temperature is increased.

5. Pressure
Thermal conductivity is not majorly dependent on pressure of substance. Pressure has a very less effect or may be no effect on it
6. Density
Thermal conductivity highly depends on density of material. Increase in density increases thermal conductivity.

7. Crystalline structure
Materials having regular crystalline structure has higher value of thermal conductivity compared to that of amorphous (irregular) form.
But among all upper factors, Temperature has great influence on thermal conductivity of material.

3. REVIEW OF RESEARCH ARTICLES:

3.1 Steady State methods:

1) Dinesh Kumar, Prakash Chandra [1]: -

This paper describes the development of a hot rod method by using water as a coolant medium which measures the heat loss through the rod for the steady state measurement of thermal conductivity of small samples. The heat flow through the test sample was essentially one dimensional and heat loss through engineering material is made to use heated guard to block the flow of heat from the hot rod to the surroundings. Experimental measurements taken in a prototype apparatus combined with extensive computational modeling of the heat transfer in the apparatus show that sufficiently accurate measurements can be obtained to allow determination of thermal conductivity of engineering material.

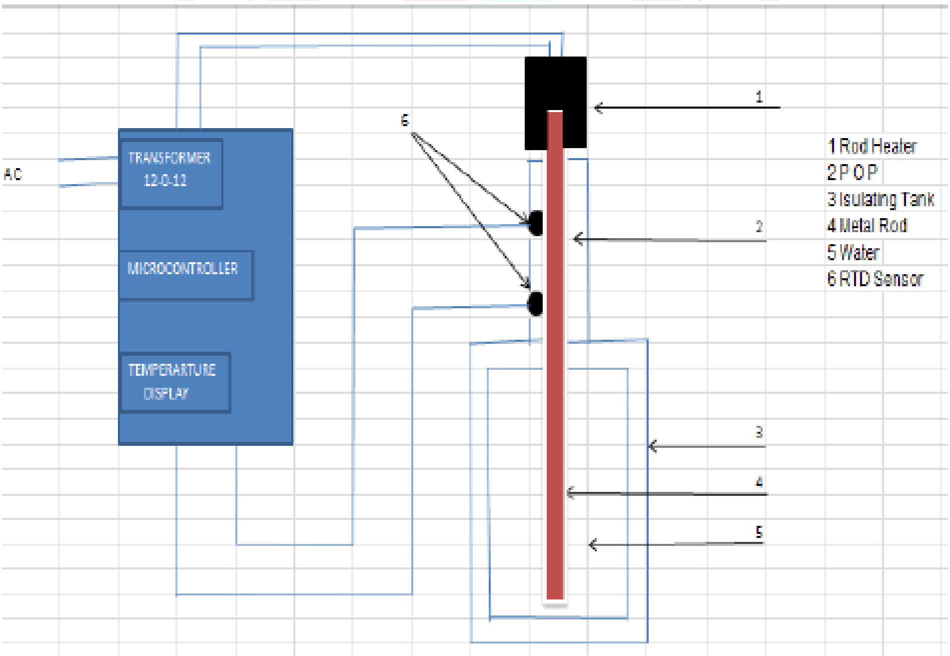

Fig.1: Schematic diagram of thermal conductivity measuring setup

2) Michael Heinrich Rausch, Kamil Krzeminski, Alfred Leipertz, Andreas Paul Fröba [2]
A versatile guarded parallel-plate instrument for the measurement of the thermal conductivity in steady state is presented. The instrument stands out due to its applicability for fluids as well as solid bodies, bulk solids, and compressible solids. A precise and automated measurement and control system for temperature and heat flow including objective criteria for identifying steady-state conditions allows convenient and accurate measurements. A comparison of results obtained for water, toluene, air, and a PTFE disk at temperatures between 308.15 K and 368.15 K with reference data confirms that uncertainties of less than 3% can be achieved by choosing adequate sample thicknesses and temperature differences between the plates.

3) N. Sombatsompop, A.K. Wood [3]

An improved Lee's Disc apparatus was designed and utilized to measure the thermal conductivity of various commercial polymers such as low-density polyethylene, polystyrene, polypropylene and poly (ether ether ketone) over a wide range of test temperatures from 40 to 400 °C. The measurements were carried out under vacuum such that convective heat losses were minimized. It was found that the thermal conductivity of semi-crystalline polymers, below melting temperature (T_m), was dependent on their density and degree of crystallinity and, above T_m, on the chain mobility and degradation effects. The thermal conductivity of the amorphous polymer was dependent on mobility of polymer chains below the glass transition temperature (T_q) and on the density above T_q The effect of density, degree of crystallinity and heating/cooling were also separately investigated and found to influence the thermal conductivity of the polymers used.

4) Robert Powell, William M. Rogers, and Don. O. Coffin [4]:

The method of determining thermal conductivity by axial heat flow through a long cylindrical sample is used. It consists of concentrically mounted sample, thermal shield, vacuum container, glass Dewar, Dewar support, and outside metal Dewar. The temperature distribution along the sample is measured by means of eight thermocouples attached to thermocouple holders positioned along the rod. Heat losses by gas convection and conduction are made negligible by evacuating the region surrounding the sample. Losses by radiation and conduction along the lead wires are reduced by enclosing the sample rod within a symmetric cylindrical thermal shield maintained at approximately the same temperature and axial gradient as the sample. Polytetra fluoroethylene is taken as a sample whose results are shown below

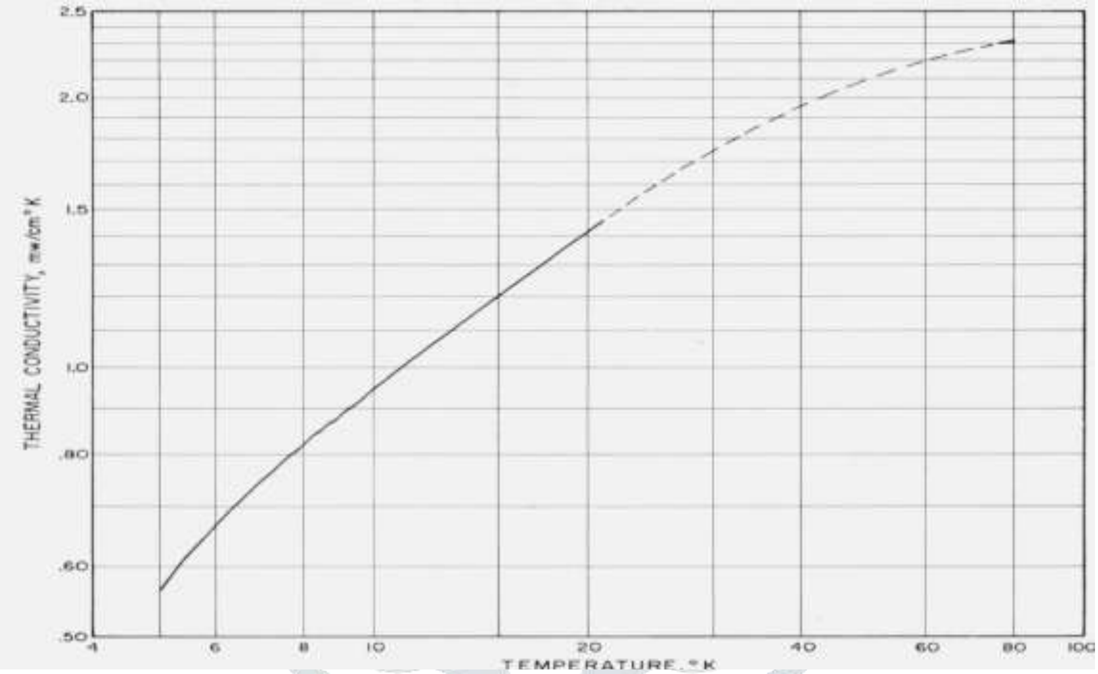

Fig.2: Measurement of Polytetrafluoroethylene

5) M. S. Van Dusen and S. M. Shelton [5]:

Apparatus for measuring the thermal conductivity of metals up to 600 C is described. The method employed consists of comparing the conductivity of a metal, either directly or indirectly, with that of lead. Determinations are made by measuring the axial temperature gradients in two cylindrical bars soldered together end to end, one end of the system being heated and the other cooled, and the convex surfaces protected from heat loss by a surrounding guard tube

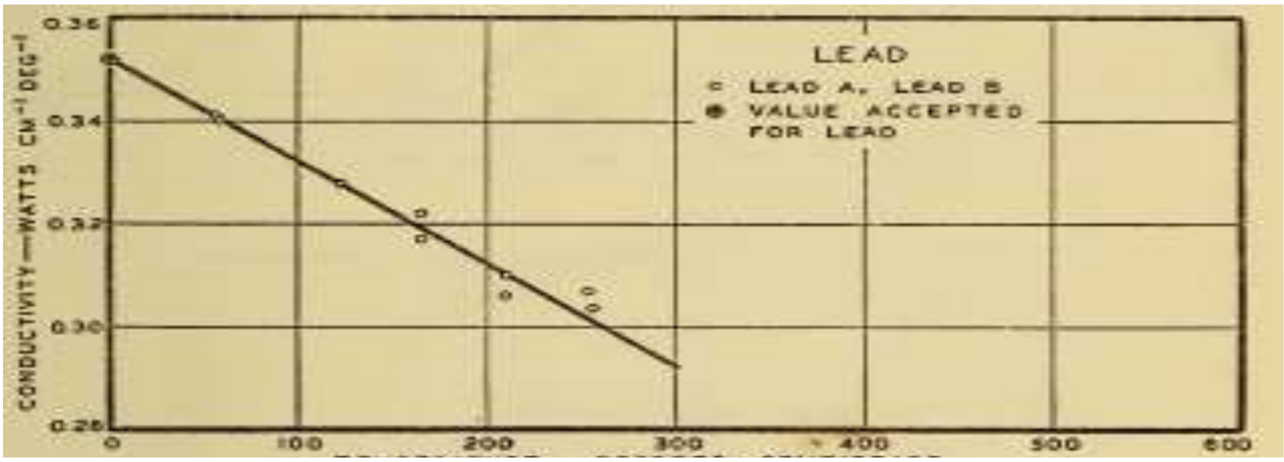

Fig.3: Measurement on Lead

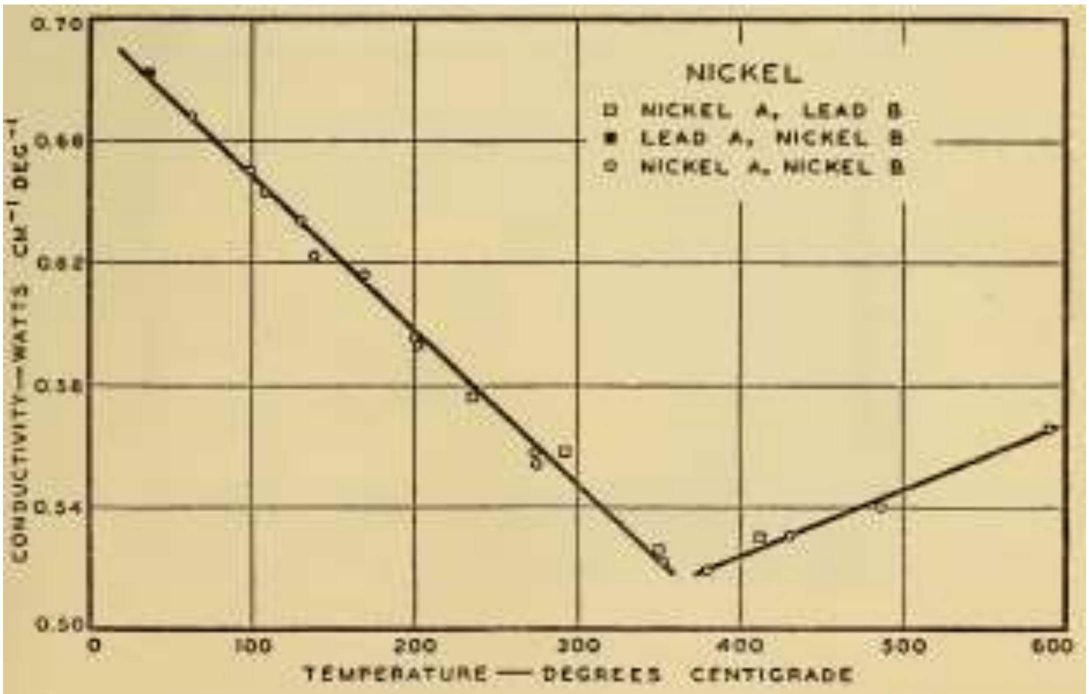

Fig.4: Measurement on Nickel

TRANSIENT METHODS: -

1) Laser flash method [6]

Xue-Hui Ana, Jin-Hui Chenga, Hui-Qin Yina, b, Lei-Dong Xiea, Peng Zhang

The thermal conductivity of high temperature liquid fluoride salt was measured by laser flash technique for the first time. A graphite crucible was specially designed to exclude the dissolved gas and avoid overflowing of molten salt; meanwhile, a special treat process was used for preparing homogeneous sample. The combined model is feasible for data analysis. The reliability of laser flash method involving crucible structure, sample preparation and data analysis is verified by distilled water and pure KNO_3 molten salt. Further, the thermal diffusivity of FLiNaK molten salt is determined to be 1.64×10^{-3}–2.48×10^{-3} cm^2/s at the temperature range of 773–973 K with the blanket atmosphere of helium. Based on specific heat capacity determined by differential scanning calorimetry (DSC) as a constant of 1.88 ± 0.08 J/g K and density measured by our group, the thermal conductivity of FLiNaK molten salt is calculated to be 0.652–0.927 W/m K with the uncertainty of ±0.023 W/m K in the temperature range of 773–973 K.

2) Transient hot wire method [7]

Joohyun Leea, Hansul Leeb, Young-Jin Baikc, Junemo Koo

While there are several factors affecting nanofluid thermal conductivity such as particle size, particle and fluid type, temperature and volume concentration, the effect of each factor on the thermal conductivity of the nanofluid is not clarified despite numerous experimental and theoretical efforts. In this work, four nanofluid samples with different particle size and volume fraction were prepared and the impact of the particle size and volume fraction on the effective thermal conductivity of the ethylene glycol/Al_2O_3 nanofluid was investigated using advanced transient hot wire system which avoids the capacitance influence and natural convection. The analysis result shows that particle size is more influential than volume fraction at the very low volume fraction less than 0.25% and the impact is more obvious with lesser volume fraction. Other than particle size and volume fraction, particle number density was turned out to be statistically very important factor affecting thermal conductivity of nanofluid when the volume fraction reaches to a certain degree of 0.2%. Under this volume fraction, the thermal conductivity of nanofluid decreases with the number density and this result may be attributed to hydrodynamic interactions induced by large fluid bodies traveling with nanoparticles in Brownian motion. This work provides not only the quantitative analyses of factors affecting the thermal conductivity of nanofluids but also the possible mechanisms of enhanced thermal conductivity.

3) 3ω-method [8]

Manuel Bognera, Alexander Hofera, Günther Benstettera, Hermann Gruberb, Richard Y.Q. Fu

The thermal conductivity λ of plasma enhanced chemical vapor deposited Si_3N_4 and sputtered AlN thin films deposited on silicon substrates were obtained utilizing the differential 3ω method. A thin electrically conductive strip was deposited onto the investigated thin film of interest, and used as both a heater and a temperature sensor. To study the thickness dependent thermal conductivity of AlN and Si_3N_4 films their thickness was varied from 300 to 1000 nm. Measurements were performed at room temperature at a chamber pressure of 3.1 Pa. The measured thermal conductivity values of AlN and Si_3N_4thin films were between 5.4 and 17.6 $Wm^{-1} K^{-1}$ and 0.8 up to 1.7 $Wm^{-1} K^{-1}$, respectively. The data were significantly smaller than that of the bulk materials found in literature (i.e., $\lambda_{AlN} = 250–285\ Wm^{-1} K^{-1}$, $\lambda_{Si3N4} = 30\ Wm^{-1} K^{-1}$), due to the scaling effects, and also strongly dependent on film thickness, but were comparable with literature for the corresponding thin films.

4) Transient line source method [9]

Shiva Kumar Modia, Durga Prasad B, M. Basavaraj

Thermal conductivity (*K*) of *Psidium guajava* L. (guava fruit) cultivar (Rayalaseema area, AP, India) is one of the fundamental importance to establish the design of process equipment. A study on effect of moisture content (MC) and temperature on thermal conductivity (*K*) of guava fruit are presented. The thermal conductivity is evaluated by transient technique using line heat source method for various MC ranging from 80% to 40% (wb) at two different densities. The analysis reveals that the thermal conductivity of guava fruit increased with increase in moisture content and temperature in the range of 0.1526 to 0.6037 W/m °C. The experimental values were compared with standard (Sweat and Anderson) models and were found in good agreement.

5) Transient plane source method [10]

Hu Zhang, Ming-Jia Li, Wen-Zhen Fang, Dan Dan, Zeng-Yao Li, Wen-Quan Tao

The thermal conductivity of film specimen is different with bulk materials and lack of standard reference materials, and few study of the measurement accuracy of film thermal conductivity has been reported. A numerical study is conducted to analyze the theoretical accuracy of film thermal conductivity introduced by the assumption of transient plane source method. In the data reduction from the measurement results, it is difficult to determine the calculation area and thickness due to the non-ideal 1D heat conduction generated in the film and the heat element has a certain thickness. The simulation found that if the thermal resistance of the film to be measured is comparable or higher than that of the sensor insulation layer, the accuracy of determining the film thermal conductivity would be very high. The theoretical accuracy of transient plane source method can be as small as ±6% after some modification.

6) Modified Transient Plane Source method [11]

Eloisa Di Sipioa, Sergio Chiesa, Elisa Destro, Antonio Galgaro, Aurelio Giaretta, Gianluca Gola, Adele Manzella

The geothermal energy applications are undergoing a rapid development. However, there are still several challenges in the successful exploitation of geothermal energy resources. A special effort is required to characterize the thermal properties of the ground and to implement the thermal energy transfer technologies. Aim of this study is to provide original heat conductivity values for rocks and sediments in regions included in the VIGOR Project (southern Italy), to overcome the existing lack of data. Thermal properties tests were performed on several samples, both in dry and wet conditions, using thermal analyzer operating following the Modified Transient Plane Source method.

7)Time-domain thermos reflectance method [12]

Jong Wook Kima, Jun-Gu Kangb, Kyung Chun Kima, Ho-Soon Yang

The thermal conductivity of $Gd_2Zr_2O_7$ films deposited on Al_2O_3 by RF sputtering is investigated by using the thermoreflectance method. In order to validate the thermoreflectance method, the thermal conductivity of $Gd_2Zr_2O_7$ films was measured by using the 3ω method with wide heater. The interfacial resistance at the interface between Au metal heater and Al_2O_3 substrate is investigated by thermoreflectance measurements of the surface of the Au heater on Al_2O_3 substrate. The thermal conductivity of $Gd_2Zr_2O_7$ films deposited on Al_2O_3 by RF sputtering show the film thickness-dependence by using thermoreflectance method. It is understood with the interfacial thermal resistance between film and substrate, and the interfacial thermal resistance between $Gd_2Zr_2O_7$ and Al_2O_3 (R_k) is $4.45 \pm 1.35 \times 10^{-8}$ m^2 K W^{-1}.

4. REFRENCES:

[1] Kumar, D., & Chandra, P. (2013). Development of Thermal Conductivity Measurement Test Rig for Engineering Material. Iosrjournals.org, 8(2), 60–66. Retrieved from http://iosrjournals.org/iosr-jmce/papers/vol8-issue2/H0826066.pdf

[2] Michael Heinrich Rausch, Kamil Krzeminski, Alfred Leipertz, Andreas Paul Froba,” A new guarded parallel plate instrument for the measurement of the thermal conductivity of fluid and solid”

[3] N. Sombatsompop, A.K. Wood,”Measurement of thermal conductivity of polymers using an improved lee's disc apparatus”,Polymer Testing, Volume 16, Issue 3, June 1997, Pages 203-223

[4] Powell, R., Rogers, W. M., & Coffin, D. O. (1957). An Apparatus for Measurement of Thermal Conductivity of Solids at Low Temperatures, 59(5), 349–355.

[5] Dusen, V. (1934). “Apparatusformeasuringthermal conductivityof metalsup to 600^{o} C”.

[6] Xue-Hui An’ Jin-Hui Cheng, Hui-Qin Yin, Lei-Dong Xie, Peng Zhang,” Thermal conductivity of high temperature fluoride molten salt determined by laser flash technique”, http://www.sciencedirect.com/science/article/pii/S0017931015007516

[7]Joohyun Lee, Hansul Lee, Young-Jin Baik, Junemo Koo’” Quantitative Analysesoffactors affecting thermalconductivityof nanofluids using an improved transienthot-wiremethod apparatus”, Http://www.sciencedirect.com/science/article/pii/S001793101500558X

[8] Manuel Bognera, Alexander Hofera, Günther Benstettera, Hermann Gruberb, Richard Y. Q. Fuc ” Differential 3ω method for measuring thermal conductivity of AlN and Si3N4 thin films” http://www.sciencedirect.com/science/article/pii/S0040609015002461

[9] Shiva Kumar Modi’ Durga Prasad B, M. Basavaraj,” Effect of moisture content and temperature on thermal conductivity of psidium guajava l. By line heat source method (transient analysis)”, Http://www.sciencedirect.com/science/article/pii/S0017931014005481

[10]Hu Zhang, Ming-Jia Li, Wen-Zhen Fang, Dan Dan, Zeng-Yao Li, Wen-Quan Tao’” A numerical study on the theoretical accuracy of film thermal conductivity using transient plane source method”, Http://www.sciencedirect.com/science/article/pii/S1359431114000647

[11] Pär Johansson’ Bijan Adl-Zarrabi, Carl-Eric Hagentoft,” Using transient plane source sensor for determination of thermal properties of vacuum insulation panels **“,** Http://www.sciencedirect.com/science/article/pii/S2095263512000684

[12]Jong Wook Kim, Jun-Gu Kang, Kyung Chun Kim’ , Ho-Soon Yang,” Measurementofthethermal conductivityof $Gd_2Zr_2O_7$ filmsby using thethermoreflectance method”, Http://www.sciencedirect.com/science/article/pii/S0040603111006289