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Lee's and Charlton's Method for Investigation of Thermal Conductivity of Insulating Materials

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Abstract : *Thermal property is the important material property for engineering and analysis of insulating materials. In this study, thermal conductivities of insulating materials are determined and compared with the literature values. Lee's and Charlton's apparatus is used to measure this property of insulating materials by steady state technique. This apparatus gives more precise result for insulators that can be utilized for the further thermal related analysis. An experimental set up is prepared to determine and analyze thermal conductivities of insulating materials. The thermal conductivities are obtained by this apparatus are 0.797W/m.K, 0.3023 W/m.K and 0.057 W/m.K for borosilicate glass, styrene butadiene rubber, and polyolefin foam faced aluminum foil respectively. The experimental results are found (9-30) % deviation from the literature values.*

Keywords - *Lee's and Charlton's apparatus, Steady State Technique, Thermal conductivity, Thermal Insulation.*

I. Introduction

Thermal conductivity is the intrinsic property of a material which relates its ability to conduct heat. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. Conduction takes place when a temperature gradient exists in a solid (or stationary fluid) medium. Conductive heat flow occurs in the direction of decreasing temperature because higher temperature equates to higher molecular energy or more molecular movement. Energy is transferred from the more energetic to the less energetic molecules when neighboring molecules collide. Thermal conductivity is defined as the quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area due to a unit temperature gradient under steady state conditions and when the heat transfer is dependent only on the temperature gradient.

The term thermal insulation can refer either to materials used to reduce the rate of heat transfer, or the methods and processes used to reduce heat transfer. Heat energy can be transferred by conduction, convection, radiation. Thermal insulation prevents heat from escaping a container or from entering a container. In other words, thermal insulation can keep an enclosed area such as a building warm, or it can keep the inside of a container cold. Insulators are used to minimize that transfer of heat energy. In home insulation, the R-value is an indication of how well a material insulates. Insulation is a material that provides a high resistance to heat flow. Examples are foamed plastics, mineral or glass fibers, cork, and foamed glass. In general, steady-state techniques perform a measurement when the temperature of the material measured does not change with time. This makes the signal analysis straightforward (steady state implies constant signals). The disadvantage is that a well-engineered experimental setup is usually needed.

II. Experimental Setup and Procedure

2.1 Experimental Setup

A Lee's and Charlton's apparatus is designed and fabricated as shown in Fig 1. A wood pattern of steam chamber (6 cm in depth, outer diameter 10 cm, inner diameter 7 cm) and disc (10 cm in diameter) is made for casting. Casting is done with cast iron and surface of the job is rough. Surface finishing is done by lathe machine and then smoothness is performed with grinding machine in MIST machine tools lab. A hole is made in the each cast iron metal disc for the insertion of thermometers to measure the temperature. Two holes are done to pass the steam into and out from the steam chamber. A water container is made by galvanized mild steel for the production of steam. Gas welding with brass is performed for joining the water container. Steam chamber, initially, is open at the top side. Joining of steam chamber is done by gas welding. A special type of stand is made to clamp the steam chamber integrated with metal disc and specimen slab. A cast iron ring is made to suspend the disc system. The whole integrated system is hanged horizontally by means of three strings from the cast iron ring. The three hooks are arranged symmetrically along the circumference of cast iron metal disc.

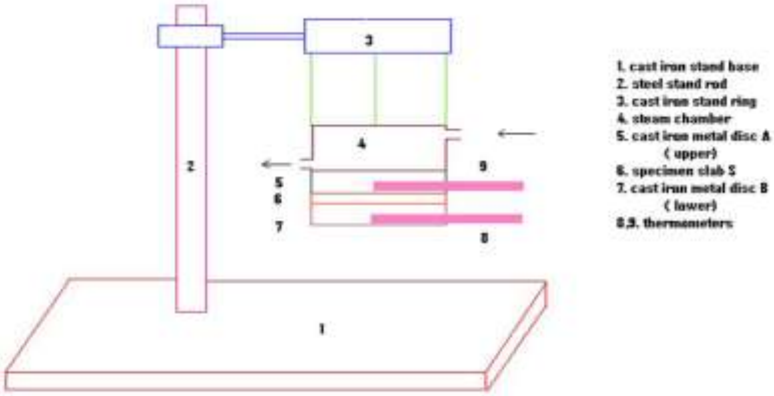

Figure 1: Schematic view of Lee's and Charlton's Apparatus

2.2 Working Procedure

(1) Mass of the cast iron metal disc B is measured. Diameter of the specimen slab S is measured with a scale. Thickness (d) of specimen slab S is measured with the help of a screw gauge. The apparatus is arranged as shown in figure3.1.The thermal contact of specimen slab S with metal disc A and B is improved by moistening it with grease.

(2) Steam is passed from a distant water container (pot) into steam chamber. The apparatus is screened off from the heat of the container. Temperatures θ_1 and θ_2 of metal disc A and B are watched respectively. When it is about to become steady, θ_1 and θ_2 are recorded at an interval of 5 minutes until they remain constant.

(3) Supply of steam is stopped and steam chamber with upper metal disc is removed. With the specimen slab S still on top of metal disc B, is heated by moving a burner under it till its temperature rises about 10℃ above the steady state temperature θ_2. Then the burner is removed and allowed metal disc B to cool. By keeping specimen slab S on metal slab B, it is ensured that metal disc B now loses heat in the same surrounding as in the first part of the experiment when it gained heat. Temperature is noted, in every half minute until the temperature falls about 10℃ from steady state temperature θ_2.

(4) Graph is drawn with the time of cooling as abscissa and the temperature of metal disc B as ordinate. A tangent is drawn at the steady state temperature θ_2. The slope of this tangent gives the rate of cooling $\frac{d\theta}{dt}$ at steady state temperature θ_2.

III. Results and Data Analysis

3.1 Thermal Conductivity Calculation

3.1.1Specimen 1 (Borosilicate Glass)

Mass of the metal disc B, m= 963 gm

Specific heat of the material of metal disc B, s=0.46 KJ/KgK

Diameter of the specimen slab S, D=10.01 cm

Area of cross-section, $\alpha = \pi \times (0.5D)^2$ sq. cm

$= \pi \times (0.5 \times 10.01 \times 10^{-2})$ sq. cm

$= 0.00787\ m^2$

Thickness of the specimen slab S, d= 0.2 cm = $0.2 \times 10^{-2}\ m^2$

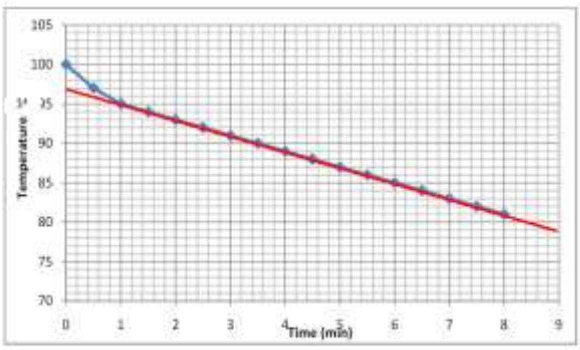

Fig 2: Temperature vs. Time for Borosilicate glass during cooling

From the cooling curve, Fig 2, the slope of the tangent at 91^0or 364K,

$$\frac{d\theta}{dt} = \frac{height\ of\ ordinate}{height\ of\ abscissa}$$

$$= \frac{97-79}{540-0}$$

$$= 0.033^0 c/sec$$

Calculation:

Thermal conductivity of borosilicate glass is measured as follow:

$$K = \frac{ms\frac{d\theta}{dt}d}{\alpha(\theta_1-\theta_2)}$$

$$= \frac{0.963\times0.46\times1000\times0.033\times0.2\times10^{-3}}{.00787\times(96-91)}\ W/mK$$

$$=0.797\ W/mK$$

3.1.2 Specimen 2 (Styrene Butadiene Rubber)

Mass of the metal disc B, m= 963 gm

Specific heat of the material of metal disc B, s=0.46 KJ/KgK

Diameter of the specimen slab S, D=10.01 cm

Area of cross-section, $\alpha = \pi$ x $(0.5D)^2$ sq. cm

$= \pi$ x $(0.5x\ 10.01x\ 10^{-2})$ sq. cm

$= 0.00787\ m^2$

Thickness of the specimen slab S, d= 0.2 cm

$=0.2x\ 10^{-2}m^2$

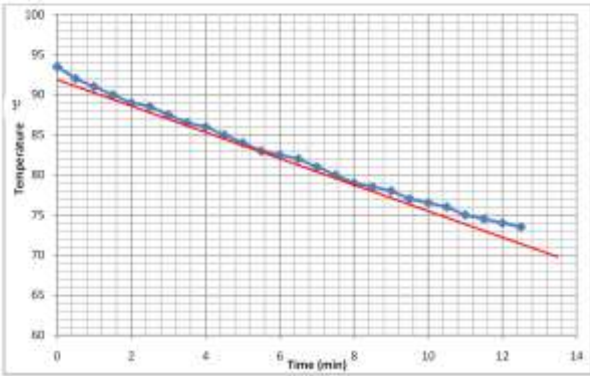

Fig 3: Temperature vs. Time for Styrene Butadiene Rubber during cooling

From the cooling curve, Fig 3, the slope of the tangent at 83.5^0 or 356.5K,

$$\frac{d\theta}{dt} = \frac{height\ of\ ordinate}{height\ of\ abscissa}$$

$$= \frac{92-70}{780-0}$$

$$= 0.0282^0 c/sec$$

Calculation:

Thermal conductivity of Styrene Butadiene Rubber is measured as follow:

$$K = \frac{ms\frac{d\theta}{dt}d}{\alpha(\theta_1-\theta_2)}$$

$$= \frac{0.963\times0.46\times1000\times0.0282\times0.2\times10^{-3}}{0.00787\times(94-83.5)}\ W/mK$$

$$= 0.3023\ W/mK$$

3.1.3 Specimen 3 (Polyolefin Foam faced Aluminum Foil)
Mass of the metal disc B, m= 963 gm
Specific heat of the material of metal disc B, s=0.46 KJ/KgK
Diameter of the specimen slab S, D=10.01 cm
Area of cross-section, $\alpha = \pi \times (0.5D)^2$ sq. cm
$= \pi \times (0.5 \times 10.01 \times 10^{-2})$ sq. cm
$= 0.00787\ m^2$
Thickness of the specimen disc S, d= 0.2cm=$0.2\times10^{-2}\ m^2$

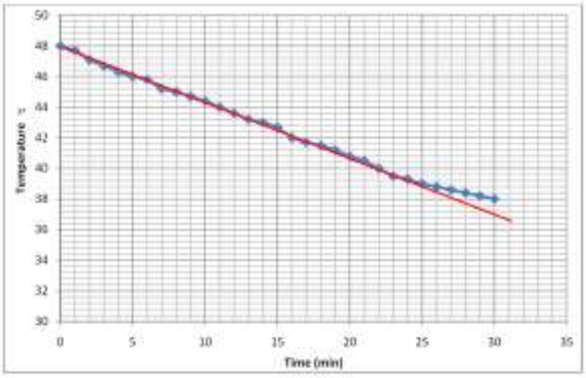

Fig 4: Temperature vs. Time for polyolefin foam faced aluminum foil during cooling.

From the cooling curve, Fig 4 the slope of the tangent at 43^0 or 316 K,

$$\frac{d\theta}{dt} = \frac{height\ of\ ordinate}{height\ of\ abscissa}$$
$$= \frac{48.3-37.5}{1800-0}$$
$$= 0.006^0 c/sec$$

Calculation:
Thermal conductivity of polyolefin foam faced aluminum foil is measured as follow:

$$K = \frac{ms\frac{d\theta}{dt}d}{\alpha(\theta_1-\theta_2)}$$

$$= \frac{0.963\times0.46\times1000\times0.006\times0.2\times10^{-3}}{0.00787\times(96-43)}\ W/mK$$

$$= 0.057\ W/mK$$

3.2 Thermal Conductivity Analysis

In this section the experimental result and graph are compared with theoretical and equation based method. It also covered the amount of deviation occurs between the experimental and equation based analysis, which are done in transient and analytical manner. To compare the experimental to theoretical magnitude of thermal conductivity, the analysis of graph came into the focus. For a particular value of temperature (steady state) it has been seen that the result of thermal conductivity in equation and experimental are different. In case of steady state method, when it is assumed to become steady in temperature, data are taken for cooling rate. That implies the result of thermal conductivity only on steady state temperature. Transient method are to be used in the study of transient heat transfer, density and specific heat have to be found independently. This process is combined with thermal conductivity to find the thermal diffusivity. For testing dry specimen it is recommended to use steady state method. In case of moist materials transient method is more suitable.

3.2.1 Analysis for specimen 1 (Borosilicate glass)

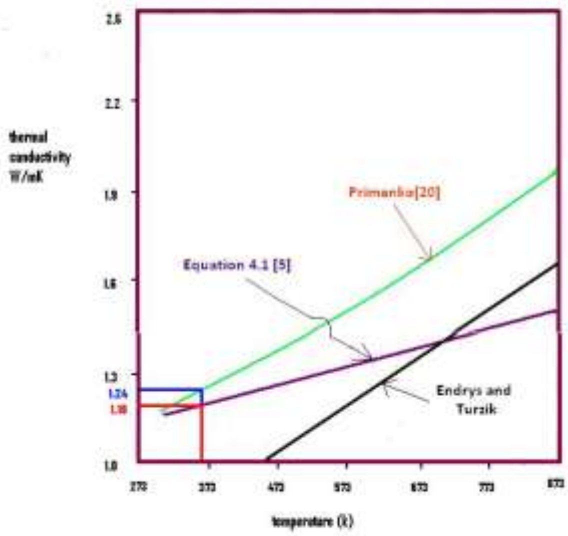

Fig 5: Determined True thermal conductivities of glass with variation on Temperature.

The true thermal conductivity data presented in Fig. 5 was determined by matching the dynamic temperature data obtained from the transient tests with the predicted temperatures from the energy model. The thermocouple readings on each side of the plate were used as boundary conditions in the energy model solution. The deviations in the calculated thermal conductivities from plate to plate are assumed to be from three sources. The temperature dependence of thermal conductivity of glass is proposed by equation (1) as follow:

$$K(T) = 1.14 + 0.000628T \quad (1)$$

Table 1: Comparison of thermal conductivity of borosilicate glass

Approach	Thermal conductivity (W/mK)	Deviation with Primenko[20] (%)	Deviation with Equation(4.1)[5] (%)
Experimental	0.797		
Primenko [20]	1.24	35.73	32.46
Equation(4.1)[5]	1.18		

Table 1 shows the variation of thermal conductivity between experimental and literature values. The deviation with experimental values is 35.73% and 32.46% respectively. A different factor depends with this deviation. The main factors are temperature and thickness. In the experiment thickness used is 0.2cm but in case of literature thickness were 0.676cm and 1.17cm. It is also for temperature. The applied transient method is highly dependent on temperature. At a particular temperature the obtained thermal conductivity will not close to the literature values. The largest factor in the determination of the thermal conductivity is the value of specific heat. A 10% uncertainty in the specific heat will cause nearly a 20% uncertainty in the thermal conductivity.

3.2.2 Analysis for specimen 2 (Styrene Butadiene Rubber)

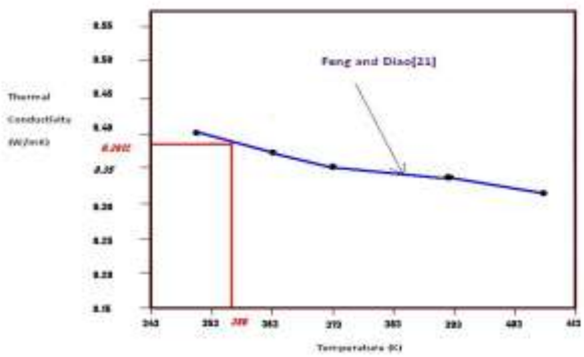

Fig 6: Relation of thermal conductivity and temperature of Styrene butadiene rubber.

Fig 6 shows the thermal conductivities of Styrene butadiene rubber at various temperatures. At low content of particles, the thermal conductivities of rubber composites change little with temperature, ranging from 75^0 to 135°C (348K to 408K). However, a slight decrease can be observed. The reason is that transmittance of thermal vibration is somewhat disturbed when the distance of macromolecular lattices is widened because of thermal expansion of the rubber. At high content of particles, the thermal conductivity of composite decreased greatly. This is because formed conductive chains are cut or shortened when thermal expansion of the rubber widens the distance between particles while it decreases the thermal conductivity of the rubber itself.

Table 2: Comparison of thermal conductivity of styrene butadiene rubber

Approach	Thermal conductivity (W/mK)	Deviation with analytical[21] (%)
Experimental	0.30234	20.69
Analytical[21]	0.3812	

It is seen from Table 2 that the results are deviated for experimental with analytical values. The results are obtained for Styrene butadiene rubber with temperature range of 70-140^0 (348K to 413K) and fibre volume fraction of 24.1%. In experimental results only constant temperature are taken into focus. If only a particular temperature is taken results will be much more deviated than the literature one. Thermal conductivity also depends on other factors along with temperature including porosity, density, specific heat, pressure. In experiment these factors were not considered.

3.2.3 Analysis for specimen 3: (Polyolefin Foam faced Aluminum Foil)

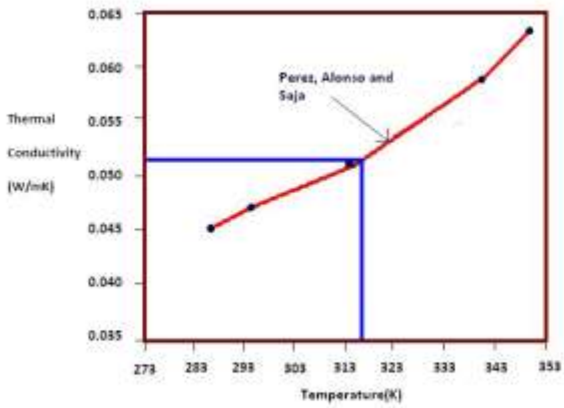

Fig 7: Experimental thermal conductivity as a function of the temperature, Alveolit samples of insulation foam.

Fig 7 shows relation between thermal conductivity and temperature, Alveolit samples of insulation foam. The thermal conductivity of a two-phase material is, of course, not a true property definable on a microscopic scale. It is rather an average property for bulk specimens, defined in terms of experimentally measurable quantities. Thermal conductivity is one of the most important functional parameters in the application and use of cellular plastic.

As is well known, it is possible to enhance the insulating behavior of foams by using low-density materials even though there are some practical limitations to this, both in the fabrication process and in the fulfillment of some basic mechanical requirements.

It is observed that the analytical value for the thermal conductivity is 0.052 W/mK and by experiment it was found to be 0.057 W/mK.

Table 3: Comparison of thermal conductivity of Polyolefin Foam faced Aluminum Foil

Approach	Thermal conductivity (W/mK)	Deviation with analytical[22] (%)
Experimental	0.057	9.62
Analytical[22]	0.052	

It is observed from Table 3 that the results are deviated with literature values. This is because the literature results are performed in case of temperature dependence thermal conductivity (transient approach).In case of transient method by changing temperature range thermal conductivity can be obtained. As the temperature increases thermal conductivity increases. In case of steady state method, when steady state temperature obtained only then cooling rate is taken. That is why the results are deviated with the literature values.

3.3 Comparison of Thermal Conductivities of Borosilicate glass, Styrene Butadiene rubber and Polyolefin foam faced Aluminum foil:

From the experiments, thermal conductivity of Polyolefin foam faced Aluminum foil (0.057 W/mK) is found significantly less than the Styrene Butadiene rubber (0.302 W/mK) and borosilicate glass (0.797 W/mK). Thus it acts as the best among these three insulating materials.

Table 4: Comparison of thermal conductivities of Borosilicate glass, Styrene Butadiene rubber and Polyolefin foam faced Aluminum foil

Insulating Materials	Thermal Conductivity(W/mK)
Borosilicate glass	0.797
Styrene Butadiene rubber	0.302
Polyolefin foam faced Aluminum foil	0.057

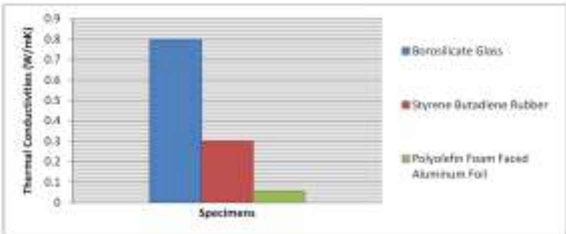

Figure 8: Comparison of thermal conductivity of Borosilicate glass, Styrene Butadiene rubber and Polyolefin foam faced Aluminum foil.

IV. Conclusion

The conclusions are drawn from obtained experimental results.

Thermal conductivity of Borosilicate glass, Styrene Butadiene rubber and Polyolefin foam faced Aluminum foil found from experimental results are 0.797 W/mK, 0.302 W/mK. and 0.057 W/mK. respectively. The deviation of experimental results from literature results is in 9% to 30%. It is found that Polyolefin foam faced Aluminum foil is good insulator among these three specimens.

[A simple and accurate apparatus for the determination of thermal conductivity was built and used to investigate the effect of processing and composition on the heat transport behavior of borosilicate glass, styrene butadiene rubber and polyolefin foam faced aluminum foil.

Reservations surrounding the application of idealized theories to interpretations of experimental data for physically imperfect materials inevitably qualify the value of deductions based upon them. In spite of this limitation, in addition to augmenting the relatively few data available for the thermal conductivity of borosilicate glass, styrene butadiene rubber and polyolefin foam faced aluminum foil; the present experimental results have served to confirm a number of expectations based upon analytical treatments of thermal conduction in specimens. A comprehensive appraisal of the standing of theoretical models must await the production of more nearly structurally perfect materials and improvements in experimental precision and accuracy. Meanwhile it may be concluded from the self-consistency of the interpretations examined that the degree of understanding afforded by analogous treatments provides encouragement for the further parallel development of experimental and theoretical investigations in this field.]

Nomenclature

Notation	Definition
q	Heat flux
K	Thermal Conductivity
T	Temperature
t	Time
L	Lorenz number
m	Mass of cast iron metal disc
s	Specific heat of metal disc

D	Diameter of the specimen slab
d	Thickness of the specimen slab
$\theta 1$	Temperature of upper metal disc
$\theta 2$	Temperature of lower metal disc
α	Cross section area of specimen slab

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