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Thermal Conductivity Study of South East Nigerian Woods Using Steady State Conditions on the grain directions

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ABSTRACT

This study investigates the anisotropic property of selected wood sample from rain forest zone (south eastern part) of Nigeria. Using an experimental rig constructed for the purpose which is called modified lee-disc. The experimental investigations of five selected wood samples were done, heating each from longitudinal and at right angle (Radial) to the grain direction of each wood sample. The thermal conductivity value 'K' along (Longitudinal direction) grain directions of 0.12 – 0.143w/mk^{-1} were obtained, while in the perpendicular direction (Radial direction) to the grain values of 0.08 – 0.12w/mk^{-1} were obtained equally. It is observed that lower conductivity values occur at the perpendicular direction (right angle) to the heat source.

Keyword; Steady state, thermal conductivity, Nigerian woods.

INTRODUCTION

Wood is hard fibrous tissue and organic material found in many plants. Natural composite of cellulose fibers -with strong tension capability rooted in a matrix of lignin which repels compressive force. Wood also may be stated as other plant materials that has equivalent properties, and to any other material gotten from wood, or wood panels, chips and fiber. The conduction of heat through wood and wood based materials has been well understood since the time of Fourier. The conduction of heat across south eastern Nigerian woods is less understood, especially since this phenomenon has received little attention until investigations to alternative building materials starts to develop as a result of high cost of concrete and iron based materials. Wood and wood-based materials have many applications in areas that require good insulating properties. In building construction, wood as a building material is of special concern because of its low thermal conductivity and good strength. The poor heat conductance of wood is due to the paucity of free electrons which are media for energy transmission and due to the porosity of wood. Wood is a typical a permeable raw material. Its structure is complicated which makes it a strong anisotropic material in the area of drying shrinkage and mechanical applications. The complicated structures of wood consist of many cell types which have a cell wall surrounding a cell lumen in the center. Also the arrangement of wood cells in two main directions, in longitudinal direction as the tree grains direction and radial-transverse direction-perpendicular to the grain direction. It is this structure that makes its physical and mechanical properties directionally dependent- anisotropic nature of wood. [1] Thermal conductivity of wood as a result of changes or differences in a grain direction, with defects and also with moisture content in the wood in the direction of heat flow. Therefore, to get the thermal conductivity of a particular wood we have to consider the combination of the variances: the thermal conductivity values of the substance in wood, the theoretical models for examining the relationship of wood structure and the experimental rig and instrumentations to be used. Thermal conductivity of wood is usually measured by the one-dimensional steady state method, two –dimensional and transient methods, but this research is focusing on the two dimensional steady-state method using linear regression method. With the moisture content available in the wood, equilibrium will take longer time to be reached. It is not quite realistic conducting the test with the moisture content available. Understanding the theory behind the wood's thermal conductivity, it makes it possible to predict its property changes with extended range of moisture content of the wood sample. Therefore, theoretical model can be step up on dry wood samples. In the processing of wood like kiln-drying, impregnation, hot pressing etc, knowing the thermal conductivity of the wood sample is of a very big essence as long as the process involves high temperature range. Thermal insulators are those materials that are poor conductors of heat. Wood is a typical example of an insulator (heat).

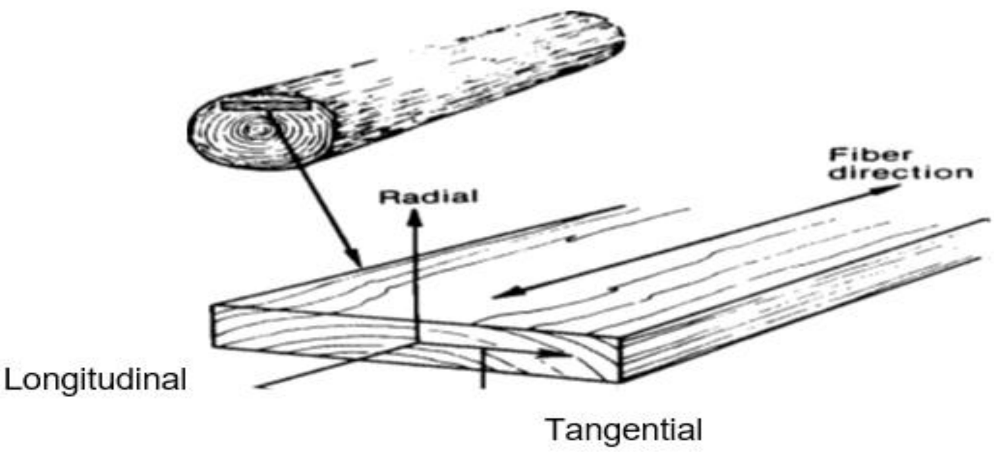

Figure 1: Three main axes of wood with respect to grain direction and growth ring.

Literature/Theoretical Underpinning

Orthotropic and anisotropic are some of wood's attributes as an engineering materials [2] They conducted a study on the thermal conductivity for uniform density of wood cells Because of the orientation and property of the wood fibers and the manner in which a tree increases in diameter as it grows, properties vary along three mutually perpendicular axes: longitudinal, radial, and tangential Figure1. The longitudinal axis and grain direction are in parallel, the radial axis normal to the wood's growth rings and perpendicular to the grain direction and the tangential axis of the wood is tangent to the growth rings and perpendicular to the grain direction. In comparative analysis, wood's properties differ in each of these direction s and axis, but the main difference is between radial and longitudinal axes. [3] in their work thermal properties of wood and wood panel products for use in buildings still talked about the two major properties affecting the thermal conductivity of wood - density and moisture content. They also dealt with the percentage water content in a wood. [4] still talked about the two major properties affecting the thermal conductivity of wood - density and moisture content. They also dealt with the percentage water content in a wood. In his work another method of finding thermal conductivity was used. They used what is called cut-bar thermal conductivity facility. The main aim was not to get the thermal conductivity, rather to get the contact conductance of cylindrical shape inner and outer interfaces [5]. The same Fourier's law was used, with known temperature distribution in the inner and outer cylinders. Another literature had their research on thermal properties of wood, gypsum and insulation at elevated temperature. [6] objective was to support the expansion of fire resistance models concept for wood and wood panels. There are so many other literatures that were reviewed in the course of this work.

Theory of Heat Equation

From a generalized 3-dimensional unsteady state equation we drive Fourier steady state equation; whenever temperature gradient exists in a body or a system, heat will flow from the higher temperature region to the lower temperature region at a rate proportional to the temperature gradient i.e.

$$\frac{q}{A} = \alpha \frac{\delta T}{\delta X} \quad (1)$$

$$q = -KA\frac{\delta T}{\delta X} \quad (2)$$

At steady state $\frac{\delta T}{\delta X} =$ (3)

At steady state and if there are heat sources into or heat-sink out of the body: -

Then; Energy balance becomes; Energy in + energy generated/lost = δu + energy out

Where δu = change in internal energy. Thus:

$$Q = -KA\frac{\delta T}{\delta X} \quad (4)$$

$$\text{Energy generated} = qA\delta x \quad (5)$$

$$\Delta U = \rho Cv\delta T\delta XAdx \quad (6)$$

$$\text{Energy out} = -KA\delta T\delta X)_{x+dx} = -A\frac{\{K\delta T}{\delta X} + \frac{\delta}{\delta X}(K\delta T/\delta X)_{dx\}} \quad (7)$$

Thus, $q + \delta x(\frac{K\delta T}{\delta X}) = \rho Cv\delta T\delta X$ (8)

From which $q + \frac{K\delta^2 T}{\delta X^2} = \rho Cv\frac{\delta t}{\delta x}$

For a 3- dimensional heat flow and with no internally generated heat:

$$\frac{K\delta^2 T}{\delta X^2} = \rho Cv\frac{\delta T}{\delta X} \quad (9)$$

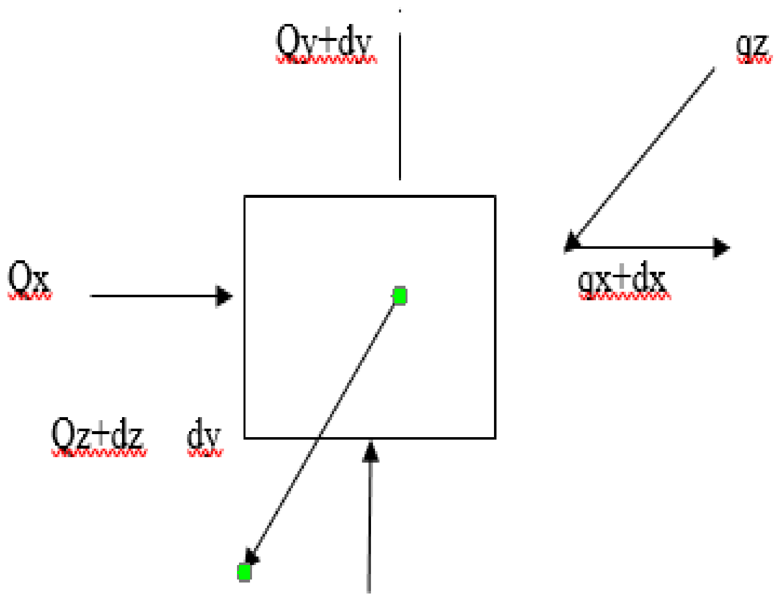

Figure 2: 3D analysis of heat flow

Thus, for

3D: $K\left(\frac{\delta^2 T}{\delta X^2} + \frac{\delta^2 t}{\delta y^2}]' + \frac{\delta^2 t}{\delta z^2}\right) = \rho Cv\frac{\delta t}{dx}$ (10)

Or $\delta^2 T = \frac{\delta^2 T}{\delta X^2} + \frac{\delta^2 t}{\delta y^2} + \frac{\delta^2 t}{\delta z^2} + \frac{q}{k} = \frac{1}{\alpha\delta t/\delta x}$ this is the vertical divergence of temperature, with internal heat generation q. Where $\alpha = \frac{k}{\rho c}$ = thermal diffusivity. Having generated this equation Fourier's steady state equation is chosen since our δt/δx =0, therefore the equation (9) after transformation is given by;

$$K = \frac{\Delta Q}{A\Delta t}\frac{x}{\Delta T} \quad (11)$$

Where ΔQ is the quantity of heat, Δt is the time rate of change through a thickness x, in a direction normal to a surface of area A, per unit area of A. Due to a temperature difference ΔT, assumptions are: under steady state conditions and heat transfer is reliant on only on the temperature slope. Alternatively, it can be thought of as a flux of heat (energy per unit area per unit time) divided by a temperature gradient (temperature difference per unit length)

METHODOLOGY

In order to evaluate the thermal conductivity of Nigerian woods, through a triangular interface and pyramid volume, a known thermal conductivity apparatus was modified - lee disc was re-designed to obtain data over a temperature range of Nigerian wood samples and under some certain thermal conditions. The primary influence of the modified lee disc (as it was called after re-design) is that the materials are locally sourced. These materials are readily available at the common Nigerian markets and could withstand the experimental temperature range without giving way for the samples first. These materials are also in relatively wide use, somewhat easy to machine and weld. The dimensions of all the materials -- U-channel iron part A and B (460mmx 40mmx25mm) stand and u-channel iron part C--(355mmx40mmx25mm) used as the base, flat iron bar part F –(204x38x5mm) used as the handle, M12 x 120mm long bolt and nut were used for fastening the handles. All these dimensions were determined after considering the constraints of available space for the selected wood samples, also the u-channel for the base was also dimensioned based on the total dimension of the electric iron and the sample material and the space to screw them together. There is an iron pipe of 127mmx 65mm diameter used to hold the electric iron and the wood sample as you tighten the handle of the apparatus [7]. A work bench of 3120x6180x614mmwas provided to create ergonomic and for the other instruments like thermocouple, ammeter and voltmeter to rest on it. Lee disc was chosen from the list ofso many other methods, because other methods are either for good conductors, out of temperature range or even complex, unreliable and unavailability of the material for design. Also the fact that this modified lee disc can be used for other heat source shapes like circle for experiments is an added advantage. For rigidity welding was used to join the u-channels to each other while nut and bolt were used to fasten the apparatus to the laboratory table. In appendix 1, bears the working drawing of the modified lee disc.

Heat was supplied to the assembly by Q-link manufacturing company with a triangular shaped 210 x110mm electric iron of 1100w capacity, Too avoid heat loss; the wood samples were cut in the same shape with the electric iron of triangular shape and coated with fiber glass heat insulator, with a little dimensional difference. The heat source is from mains of supposedly 240v.

$$P = IV \qquad (12)$$

Where Q = P representing applied heat.

Instrumentation: The calculation of thermal conductivity of woods and other materials involves the use of some instruments to acquire some vital data needed for the calculation. Some of the instruments used are;

Thermocouple: Type K thermocouple was used. The range is -323k to 1573k with tolerance of ±0.75%. K- Type is described as 3.24x150mm metal sheath 100cmcompensating wire.

Thermometer: TES- 1303 digital thermometer for the thermocouple (probe) above was used. This digital temperature sensor used followed NBS and IEC 584 temperature /voltage standard table for K-type thermocouple. Dimension of the temperature sensor includes; 135(L) x 72(W) x 31(H) mm and 235g weight with battery and has a display rate of approximately 2.5 times per second.

Ameter: Analog AC ammeter of 0-25amps measurement ranges was used to measure the current that is supplied to the heater.

Volmeter: Also an analog AC voltmeter range of 0- 500volts was used to measure the voltage coming to the heater.

Meter Rule: This was used to measure the distance of the two probes (thermocouples) and also helped in measuring the width and the height.

Thermal Conductivity

The thermal conductivity of the materials used in this investigation was determined by means of the modified lee disc method. This method, as employed in this investigation, imposes a flow of heat through a triangular shaped wood samples. The samples and the heat source are placed together, and heat is introduced at one end of the surface of the samples and removed at the other end of the sample [8]. The heat applied, the temperature difference and the thermal conductivity were calculated using linear regression equation for two samples prediction of thermal conductivity at any distance on the sample. Fourier's Law was used to determine the thermal conductivity of the samples for the anisotropic behavior of wood. Each sample has two pieces each of different grain direction

The schematic diagram and the picture of the experimental test rig are shown in figure 3 and plate 1.

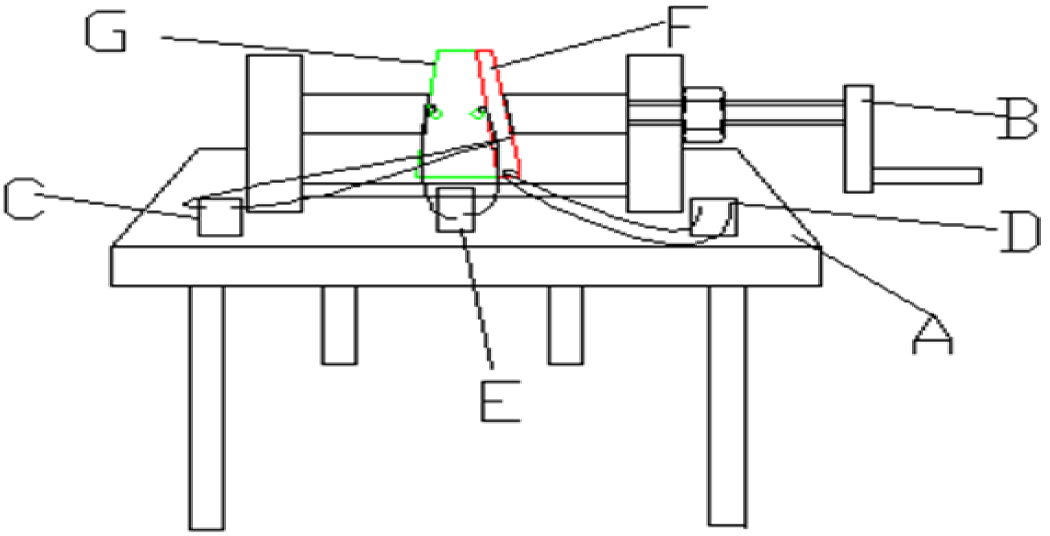

Figure 3. Schematic Diagram of modified lee disc apparatus

Keys to the Schematic diagram above

A – Laboratory Table
B – Modified Lee Disc Apparatus
C – Ammeter
D – Voltmeter
E – TES-1303 Digital Thermometer with Type-K Thermocouple
F – 1.5kw Power Source
G – Wood Sample

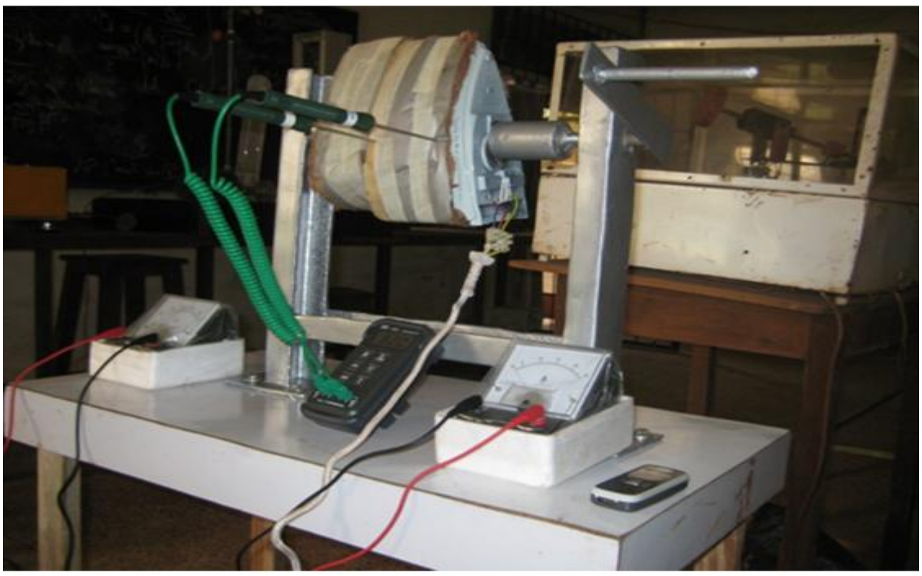

Plate 1. Photo of the experimental set up of modified lee disc apparatus

Sample Characterization

As mentioned earlier the five selected samples used for the steady state method of determining the anisotropic property of wood were chosen due to their availability in the market and their rampant usage in Nigeria. All the samples are of the same shape-triangular. Their dimensions vary with average value of ± 3mm. Melina (Gmelina Arborea), Mahogany (Swietenia Macrophylla),wall-nut (Genus Juglans),Inyi (Family of Bignoniaceac) and Agba (Prioria Balsamifera) are the names of the wood samples used [9]. Each of these samples has their different grain direction from the applied heat. Longitudinal direction is measured 180^0 to the grain direction while radial direction is measured 90^0 to the grain direction.

Steady State Testing

Before the heater element and the mains, an ammeter (in series) and a voltmeter (in parallel) were placed. For good contact with the probes and the wood samples a little oil was added in the holes. Voltage and the current were held steady. They were heated until the temperature of probe 1 and probe 2 became steady, while differences in the temperature were measured every 15minutes time interval. This means that the heat in to the surface every minute is the same to the heat out of the end surface of the wood sample every minute. We assumed that there is no heat loss since our dx is small and fiber glass was used to coat the samples. All conductivity measurements were taken while the specimens were at steady state. Steady state was ascertained by timing with a clock to know when the variation of the control parameters and the measured value does not exceed our specified drift tolerance range for fifteen minutes for this experiment.

The selection of the heater settings is influenced by the maximum temperatures. The epoxy used to pot the thermocouples softens at elevated temperature (at least, until it is completely out-gassed), but since no strain was applied to the wire this was not taken into account to determine the over-temperature condition. The temperature used to determine if an over-temperature condition existed was 823k, ensuring that none of the components or instrumentation was damaged. Preliminary testing of the test facility revealed that maximum heater settings could be used without violating the over-temperature criteria. Therefore, all testing includes the maximum heater setting. But the rheostat in the electric heater was supposed to help us to regulate the heat applied, to avoid burning the wood. Fourier steady state equation was applied since our dt/dx = 0 the use of steady state equation of 10 was possible [10]. Here below is our table and values were obtained from test measurements and calculations.

Table 1*:* Experimental data from the modified lee disc using steady state.

Samples	Grain direction	(dx) Probe distance (m)	Area (A) M^2	δT T1-T2 (K)	Density (ρ) g/m^3	Thermal conduc. K (W/MK^{-1})
Agba	Longitudinal180	0.072	0.013	330.4	1643	**0.13**
	Radial90^{0}C	0.043	0.012	350.4	1427	**0.08**
Inyi	Longitudinal180^{0}C	0.064	0.013	298	2911	**0.14**
	Radial90^{0}C	0.062	0.012	340.8	3057	**0.12**
Melina	Longitudinal180^{0}C	0.076	0.013	352.4	1251	**0.13**
	Radial90^{0}C	0.066	0.012	365.3	1574	**0.12**
Mahogany	Longitudinal180^{0c}	0.065	0.012	331.4	1917	**0.13**
	Radial90^{0}C	0.058	0.013	347	1950	**0.10**
Tick (Wallnut)	Longitudinal180^{0c}	0.063	0.013	330.9	2270	**0.12**
	Radial90^{0}C	0.072	0.013	358.7	2280	**0.12**
Mean values		**0.063**	**0.013**	**342.8**	**2028**	0.13

Comparing the values of 'K' in the literature it shows that they are between the established values of thermal conductivity of wood, which is from 0.001 → 0.4. However, some literature has the value less. During the test the mean values of 'I' and 'V' are 0.035amps and 230 respectively. Area; from the triangular shaped sample the area was calculated using area of a triangle

$$\frac{1}{2}xbxh \qquad (13)$$

Density; The weight of the wood samples was weighed with scale and the volume of a pyramid was used in calculating the volume.

$$\frac{1}{3}xbxhxl \qquad (14)$$

And the density is the mass per unit volume of the samples Kg/m^3

The applied heat source from the mains is gotten from the electrical relations of equation 12

Therefore, the thermal conductivity is given by the same Fourier's law of equation (2). The equation was transposed to get the K which is what we are looking for, and we have thus;

$$K = qA\frac{\delta X}{\delta T} \qquad (15)$$

Where;**K** is the thermal conductivity unknown (w/mk$^{-1)}$, **q** is the heat applied in watt (w)

dT is the temperature difference we are measuring Kevin (K), **dx** is the distance between the probes T1 → T2 (m), **A** is the cross section area of the wood samples (m^2).Calibration of the thermocouple was made using mercury in glass thermometer, after boiling water at 373k and getting an ice block

Calibration

Before the use of the thermocouple calibration was done to confirm the measurement range of the thermocouple. Sachet water at zero temperature (blocked) and water boiled at 373k were used. Measurement was done with mercury in glass thermometer and again measured with the TES thermometer with type K thermocouple being used in this work for confirmation [11]. The range is -323k to 1573k, making the basic accuracy at 23± 278k calibration.

RESULTS

From the graph compares the longitudinal and radial grain directions of the selected wood samples.

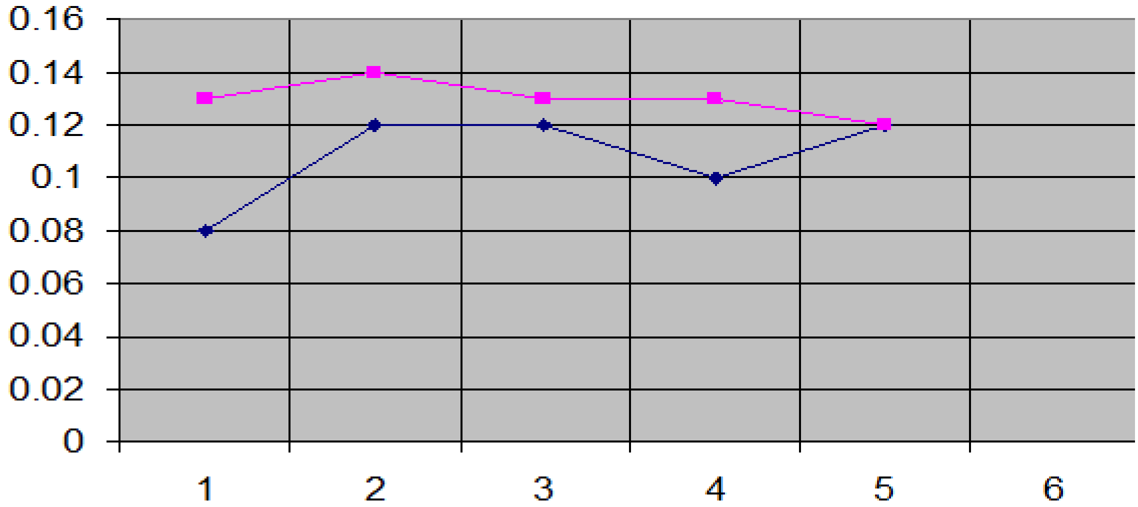

Figure 4. Comparison of longitudinal direction and radial direction

DISCUSSION

From the finding that was evident to us that the radial directions seem to be transferring heat slower than the longitudinal direction. The entire sample showed the same phenomenon. The area of the samples is plus or minus 0.001 [12]. From the results the radial line is below the longitudinal line in the graph. It comes to show that the directions of the grain have a role to play in the heat conduction of woods. This further confirms that the applied heat is 90 degrees to the radial direction which has more paucity than the longitudinal direction of 180 degrees to the applied heat

Implication to Research and Practice

Radial directions of grain growth of woods are better insulators than the longitudinal directions of wood's grain growth. This research gives first-hand information on the choice of wood we would be selecting for various projects depending on the amount of heat insulation we wish to have [13].

CONCLUSION

This study did not include the temperature and moisture content effects on thermal conductivity. Anisotropic property of wood was studied and values obtained confirm its importance while dealing with woods as an insulator. From our values it may be concluded that wood for insulation purposes are better used in the radial (perpendicular) direction of the grain growth to the heat source. Analysis shows that wood is anisotropic, also that grain directions of wood affects it conductivity.

FURTHER RESEARCH

Investigation for more grain directions in wood apart from radial and longitudinal gran directions need to be worked on. This research needs to be done on the sample with moisture content, to know the behavior of the wood when soaked in water

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