EXPERIMENTAL INVESTIGATIONS ON THERMAL CONDUCTIVITY OF NIGERIAN WOODS

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ABSTRACT

Experimental studies were carried out in order to evaluate the thermal conductivity of Nigerian wood (Mahogany, Agba and Melina), under steady-state conditions. A rig was designed to carry out the experiment for measurements of the effect of temperature and grain directions on the thermal conductivity of Nigerian woods. Experiments were carried out within a distance of holes 20*mm* effort where thermometer probes were fixed. The heating element is a carbon-steel of 10*mm* thickness of 1000*watts*. Digital thermometer is instrumented on all grain structure directions during the experimentations on each tested wood sample. The heating element is electrically heated by varying the heat input with rheostat, at interval of 20 *volts* at 20 *minutes* heating. Experiments were run at different grain structure directions of heat flow between 15 to 180 *watts*. Results obtained were analyzed by calculating for the thermal conductivity $K\ (w/m.^oC)$ in the directions of the grain for each sample. A dimensionless linear regression correlation equation were done, based on the thermal conductivity, K, and temperature, T. It was observed that by linear regression, the correlation ofthermal conductivity of Nigerian wood varies between 0.04. to 0.5 w/m^oC,under the range of temperature T between 10 to 100^oC .

The correlation for K with T: -

- $K = a + bT$
- $K_{ma} = -0.4798 + 0.0409T, -0388 + 0.388T, -0.308 + 0.0316T$
- *for wood in Radialdirection*
- $K_a = -0.389 + 0.0335T, -0.212 + 0.0229T, -0.351 + 0.031T$
- *for wood in Longitudinal direction.*
- $K_{me} = -0.205 + 0.0211T, -0.349 + 0.246T, -0.422 + 0.0321T$
- *for wood inTangential direction*

Keywords: Woods, carbon steel, thermal conductivity, digital thermometer, heating

1.0 INTRODUCTION

Wood is a hygroscopic, porous material. The unique structure of wood causes the anisotropic nature of wood in its mechanical and physical properties. Thermal conductivity of wood has been studied by many scientists.

The ability of a material to conduct heat as a result of transmitting molecular vibrations from one atom or molecule to another varies greatly depending upon the chemical nature of the material and its gross structure and texture. The thermal conductivity of wood varies in the three main directions of wood as they are usually referred to in the wood lumber industry – Longitudinal direction (parallel to the grain, along the length of a tree), Radial direction, (perpendicular to the grain, along the radius of the cross section) and Tangential direction (perpendicular to the gain, tangent to each growth ring).

The grain structure of wood in these three directions is different. Most of the anisotropic properties of wood are due to this structure difference.

The thermal conductivity of Mahogany and Agba (*hard wood*) and Melina (*in-between hard and soft*) are all in their grain directions. Their thermal conductivity was determined for all three directions (radial, tangential and longitudinal) depending on a number of factors with varying degree of importance. The more significant variable affecting the rate of heat flow in these woods are (1) Density of wood (2) Moisture content of wood (3) Direction of heat flow with respect to the grain. (6) Extractives or chemical substances in the wood and defects, etc.

1.1 CONDUCTION HEAT TRANSFER

(One dimensional)

- When a temperature gradient exists in a body, experience has shown that there is an energy transfer from the high-temperature region to the low-temperature region. We say that the energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient:

$$\frac{q}{A} \alpha \frac{\partial T}{\partial x}.$$

- When the proportionality constant is inserted

$$q = k A \frac{\partial T}{\partial x} \quad \ldots\ldots 1$$

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- where *q* is the heat-transfer rate and $\partial T/\partial x$ is the temperature gradient in the direction of heat flow. The constant k is called the thermal conductivity of the material, and the minus sign is inserted so that the second principle of thermodynamics will be satisfied i.e. heat must flow downhill on the temperature scale, as indicated in the coordinate system of *figure 1*

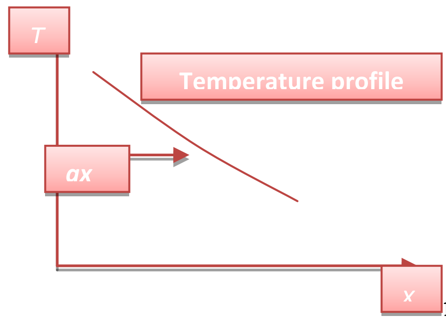

fig 1

Equation 1 is called Fourier's law of heat conduction after the French mathematical physicist Joseph Fourier, who made very significant contributions to the analytical treatment of conduction heat transfer. It is important to note that equation *1* is the defining equation for the thermal conductivity and that k has the units of watts per meter per Celsius degree in a typical system of unit ion which the heat flow is expressed in watts.

We now set ourselves the problem of determining the basic equation that governs the transfer of hat in a solid, using equation *1* as a starting point.

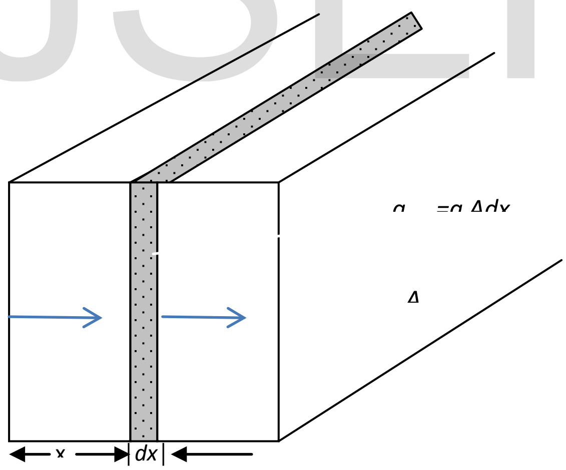

Fig 2

Elemental volume for one-dimensional heat-conduction analysis

1.2 THERMAL INSULATION

- Thermal insulation refers to the material used for the purpose of reducing the rate of heat flow. Thus its distinguishing features is low thermal conductivity, which has been defined as the time rate of heat flow through unit area of homogenous substances under the influence of a unit temperature gradient in the direction perpendicular to the area. “Thermal conductivity is measured in *J/Sec.*m^2 *(Btu/(hr)(*ft^2*)* Thermal conductivity varies with temperature and must be quoted at a specific mean temperature.

- To increase the comfort of living spaces
- To converse heat or some other forms of energy e.g. electrical energy to operate a refrigerator compressor.
- To facilitate control of the temperature of a process.
- To reduce the temperature of the shell of a pressure vessel.
- To control the external temperature of the insulated space in order to avoid danger to personnel.
- To protect the surrounding structural members from damage by high temperature
- To reduce the temperature of working spaces and in the case of equipment operating below ambient temperatures to prevent condensation or icing at the warmer surface.
- Depending on the application, one or the other purpose may govern the choice of insulation.

1.3 THERMAL CONDUCTIVITY OF WOOD

Wood is a hygroscopic, porous material. The unique structure of wood causes the anisotropic nature of wood in its mechanical and physical properties. Thermal conductivity has been shown by many scientists to have a very close relationship with the wood structure and moisture. The ability of a material to conduct heat as a result of transmitting molecular vibrations from one atom or molecule to another varies greatly depending upon the chemical nature of the material and its gross structure or texture. Thermal conductivity, k, is expressed in terms of quantity of heat, Q that flows across unit thickness x, of a material with a unit cross section, A under unit temperature difference between the two faces, T, in unit time, t:

$$k = \frac{Q * x}{A * T * t} \qquad \ldots\ldots 2$$

The heat conductivity of wood is dependent on a number of factors with varying degree of importance. The more significance variables affecting the rate of heat flow in wood are ; 1) Density of wood; 2) moisture content of wood; 3) direction of heat flow with respect to the grain; 4) relative density; 5) extractives or chemical substances in the wood, and defects, etc. from numerous and varied factors affecting thermal conductivity of wood, Van Dusen first found that there was nearly a linear relationship between conductivity and density. So did Rowley.

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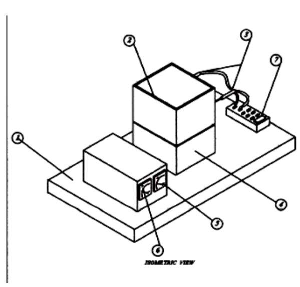
2.0 DESIGN AND CONSTRUCTION OF THE RIG.

2.1 OVERVIEW OF THE RIG

The design of the system is single sided. It is capable to test one fixed size specimen at a time. The system uses “electric heating element method” to determine the thermal conductivity of insulators and other materials of higher thermal resistance. The size and shape of the sample is historically similar to that of a standard brick with an equal companion piece used for thermal symmetry. An electric circuit is also available for regulating the heat entering the heater (electric heating element) and for reading the different values of the voltage and current entering the system. The outside body and inner chamber are fully lagged while leaving the top of the system open to ensure heat flows in one direction. There also provision of k-type digital thermometer and two k-type digital thermometer probe for measuring and taking the readings of the temperature.

2.2 THE RIG

The material used for construction of the entire body of the rig is mild steel. In other words, the materials have the same material properties in its entire body. The steel was made by oxidizing away the impurities that are present in iron produced in the blast furnace. Mild steel is a ferrous metal because it contains iron which is the major constituent and most times it forms the major component in mechanical production.



PART LIST

S/N	DSCRIPTION	MATERIAL
1	TABLE	WOOD
2	WOOD SAMPLE	WOOD
3	PROBES	
4	RIG	
5	AMETER	STOCK
6	VOLTAMETER	STOCK
7	K-TYPE THERMOMETER	STOCK

- Fig 3

The outer and inner chamber was coupled together with the aid of welding, bolts and nuts. The heating sources was fixed on the top of the inner chamber while the top of the chamber was covered with light steal plate and left unlagged for the flow of heat. Meanwhile, the entire chamber both in and out was fully lagged. Inner chamber was lagged using brick and fiber glass while the outer was lagged using fiber glass and asbestos clothing (which was used to hold the fiber glass of rig). The dimension of the rig is 180mm and 130mm of the length and breath respectively the height of the rig is 100mm.

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2.3 THE WOOD SAMPLE

The woods were cut out from the source and machined to a given profile. This process was achieved with the aid of a machine cutter with an adjustable horizontal blade. After cutting, the length and width of the woods are 0.18m and 0.13m respectively. The wood was reduced to a thickness of 0.13m with the aid of a wood saw or smoother.

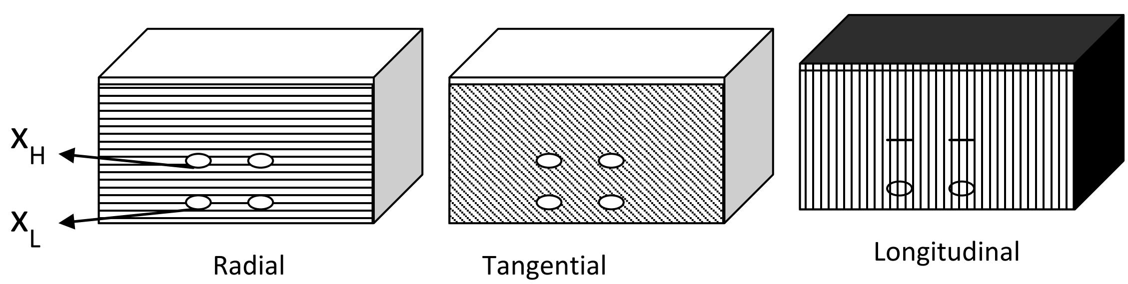
The different wood sample or test piece selected for the tests include:

Mahogany, Agba and Melina. The sample were cut into rectangular box shape. The length and width of the wood samples is 180mm by 130mm while the thickness is 130mm.

Four tiny holes of diameter 5mm and 70mm depths were drilled in the wood sample. Four holes on ach sample considering the grain structure direction. Two holes up and three holes down, all the holes are 50mm apart. The two lower holes sample while the two upper holes are of the same height from the bottom of the wood sample as well. The lower holes on the radial grain direction for each wood samples is label x_{L1} and x_{L2} while the upper holes are labeled x_{H1} and x_{H2}.

On the other side, for longitudinal grain direction, the lower holes are labeled y_{L1} and y_{L2}, while the upper holes are labeled $y_{H1}$and y_{H2}.

The holes for tangential grain direction has Z denotations; these holes are the point from which temperature readings are taken while the x_L, x_H, $y_{L,}$ y_H, z_L and z_H are the height or distance at which temperature readings are taken. x_L, $y_{L,}$and z_L is 30mm from the bottom of the wood sample, x_H, y_H, and z_H is 50mm from the bottom of the sample; d_x, d_y, and d_z is20mm.



wood sample in grain structure directions

Fig 4

Longitudinal direction (parallel to the grain, along the length of a tree), radial direction (perpendicular to the grain, along the radius of the round tree on the cross section), and tangential direction (perpendicular to the grain, tangent to each growth ring).

: Set up wood sample in laboratory

Fig 5

2.4 EXPERIMENTAL PROCEDURE

The rig was plugged to the source of power. The lagged wood sample is placed on top of the rig. The thermometer probes which were connected to the digital thermometer for taking the temperature reading is inserted into each of the X_L and the corresponding X_H. The rig is then switched on and the voltage is regulated by the rheostat to 40 volts. The ammeter reading is also taken for the corresponding current before heating the atmospheric temperature was taken. The wood sample is allowed to heat for 20 minutes and temperature at X_L and the corresponding X_H are taken from the digital thermometer. This same test was carried on each of the four holes drilled on the sample of the wood in X (radial grin direction) using the same procedure.

The same procedure or process was repeated when the voltage was increased to 60 volts, 80 volts, 100volts, 120 volts, 140 volts and 160 volts and their corresponding current for the same grain structure direction.

This experiments was carried out on radial grain structure direction X longitudinal grain structure direction Y and tangential grain structure direction Z

3.0 EXPERIMENTAL DATA

3.1 MAHAGONY EXPERIMENTAL DATA

Table 3.1: Mahogany in Radial Grain Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} ^oC	T_{L2} ^oC	T_{LM} ^oC	T_{HI} ^oC	T_{H2} ^oC	T_{HM} ^oC	T_{LM}-T_{HM} ***(dT)*** ^oC
1	40	0.4	16	37	37	37	26	26	26	11
2	60	0.5	30	40	40	40	26	26	26	14.
3	80	0.6	56	42	43	42.5	27	27	27	15.5
4	100	0.7	80	45	45	45	27	28	27.5	17.5
5	120	0.8	96	49	48	48.5	28	28	28	20.5
6	140	0.9	126	52	52	52	30	30	30	22
7	160	1.1	17.6	53	56	54.5	31	32	31.5	23

Table 3.2: Mahogany in Longitudinal Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} ^oC	T_{L2} ^oC	T_{LM} ^oC	T_{HI} ^oC	T_{H2} ^oC	T_{HM} ^oC	T_{LM}-T_{HM} (*dT*) ^oC
1	40	0.4	16	39	39	39	26	27	26.5	12.5
2	60	0.5	30	40	41	40.5	27	26	26.5	14
3	80	0.6	56	44	44	44	27	28	27.5	16.5
4	100	0.7	80	48	46	47	28	28	28	19
5	120	0.8	96	49	50	49.5	28	29	28.5	21
6	140	0.9	126	52	53	52.5	31	30	30.5	22
7	160	1.1	176	57	57	57	32	32	32	25

Table 3.3: Mahogany in Tangential Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} ^oC	T_{L2} ^oC	T_{LM} ^oC	T_{HI} ^oC	T_{H2} ^oC	T_{HM} ^oC	T_{LM}-T_{HM} (*dT*) ^oC
1	40	0.4	16	37	38	37.5	26	27	26.5	11
2	60	0.5	30	40	40	40	27	27	27	13
3	80	0.6	56	43	42	42.5	27	28	27.5	15
4	100	0.7	80	45	46	45.5	28	28	28	17.5
5	120	0.8	96	49	48	48.5	29	28	28.5	20
6	140	0.9	126	52	52	52	30	30	30	22
7	160	1.1	176	54	55	54.5	31	31	31	23.5

3.2AGBA EXPERIMENTAL DATA

Table 3.4: Agbain Radial Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} ^oC	T_{L2} ^oC	T_{LM} ^oC	T_{HI} ^oC	T_{H2} ^oC	T_{HM} ^oC	T_{LM}-T_{HM} (*dT*) ^oC
1	40	0.4	16	38	39	38.5	26	26	26	12.5
2	60	0.5	30	41	40	40.5	26	27	26.5	14
3	80	0.6	56	43	43	43	27	27	27	16.5
4	100	0.7	80	47	47	47	28	28	28	19
5	120	0.8	96	50	50	50	28	29	28.5	21.5
6	140	0.9	126	53	53	53	30	30	30	23
7	160	1.1	176	56	55	55.5	32	31	31.5	24

Table 3.5: Agbain Longitudinal Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} *°C*	T_{L2} *°C*	T_{LM} *°C*	T_{HI} *°C*	T_{H2} *°C*	T_{HM} *°C*	T_{LM}-T_{HM} (*dT*) *°C*
1	40	0.4	16	40	40	40	27	27	27	13
2	60	0.5	30	42	42	42	27	27	27	15
3	80	0.6	56	45	44	44.5	27	28	27.5	17
4	100	0.7	80	48	46	47	28	28	28	19
5	120	0.8	96	51	51	29	29	29	29	22
6	140	0.9	126	55	55	55	30	30	30	25
7	160	1.1	176	57	58	57.5	31	30	30.5	27

Table 3.6 : Agbain Tangential Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} *°C*	T_{L2} *°C*	T_{LM} *°C*	T_{HI} *°C*	T_{H2} *°C*	T_{HM} *°C*	T_{LM}-T_{HM} (*dT*) *°C*
1	40	0.4	16	38	38	38	26	26	26	12
2	60	0.5	30	41	40	40.5	27	27	27	13.5
3	80	0.6	56	43	43	43	27	27	27	16
4	100	0.7	80	48	47	47.5	28	28	28	19.5
5	120	0.8	96	51	52	51.5	30	29	29.5	22
6	140	0.9	126	55	55	55	31	31	31	24
7	160	1.1	176	57	57	57	32	32	32	25

3.3MELINA EXPERIMENTAL DATA

Table 3.7: Melinain Radial grain Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} *°C*	T_{L2} *°C*	T_{LM} *°C*	T_{HI} *°C*	T_{H2} *°C*	T_{HM} *°C*	T_{LM}-T_{HM} (*dT*) *°C*
1	40	0.4	16	41	41	41	27	26	26.5	14.5
2	60	0.5	30	45	44	44.5	27	28	27.5	17
3	80	0.6	56	47	47	47	28	28	28	19
4	100	0.7	80	50	50	50	29	29	29	21
5	120	0.8	96	53	53	53	30	29	29.5	23.5
6	140	0.9	126	56	55	55.5	31	30	30.5	25
7	160	1.1	176	59	59	59	33	31	32	27

Table 3.8:Melinain Longitudinal Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} ^oC	T_{L2} ^oC	T_{LM} ^oC	T_{HI} ^oC	T_{H2} ^oC	T_{HM} ^oC	T_{LM}-T_{HM} (*dT*) ^oC
1	40	0.4	16	42	42	42	27	27	27	15
2	60	0.5	30	46	46	46	28	28	28	18
3	80	0.6	56	50	51	50.5	29	30	29.5	21
4	100	0.7	80	56	56	56	32	32	32	24
5	120	0.8	96	61	61	61	34	34	34	27
6	140	0.9	126	65	66	65.5	36	36	36	29.5
7	160	1.1	176	69	70	69.5	38	37	37.5	32

Table 3.9: Melinain Tangential Direction

S/N	V *Volts*	I *Amp*	Q *watts*	T_{L1} ^oC	T_{L2} ^oC	T_{LM} ^oC	T_{HI} ^oC	T_{H2} ^oC	T_{HM} ^oC	T_{LM}-T_{HM} (*dT*) ^oC
1	40	0.4	16	41	41	41	26	26	26	14
2	60	0.5	30	44	43	43.5	27	27	27	16.5
3	80	0.6	56	46	46	46	28	28	28	18
4	100	0.7	80	49	48	48.5	29	28	28.5	20
5	120	0.8	96	52	52	52	29	29	29	23
6	140	0.9	126	55	55	55	30	30	30	25
7	160	1.1	176	59	59	59	32	31	31.5	27.5

4.0 LINEAR REGRESSION CORRELATIONOF K AND T

From the Fourier equation of thermal conductivity

$$K = \frac{Q}{A} \times \frac{dx}{dT}$$

$K = n + mT$, $K = a + bT$

$y = a + bx$

where $m = b$

$n = a$

apply liner regression equation

$$y = bx + a$$

where :

$$b = \frac{n\Sigma xy - \Sigma x\Sigma y}{n\Sigma x^2 - (\Sigma x)^2}$$

$$a = \frac{\Sigma y}{n} - \frac{b\Sigma x}{n}$$

$$r = \frac{n\Sigma xy - \Sigma x \Sigma y}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$

4.1 LINEAR REGRESSION CORRELATION OF K (THERMAL CONDUCTIVITY) W/M,^{O}C AND T (TEMPERATURE) ^{O}C

Fig. 6 : *Program Control Interface*

4.1.1 Program Calculation for (a)

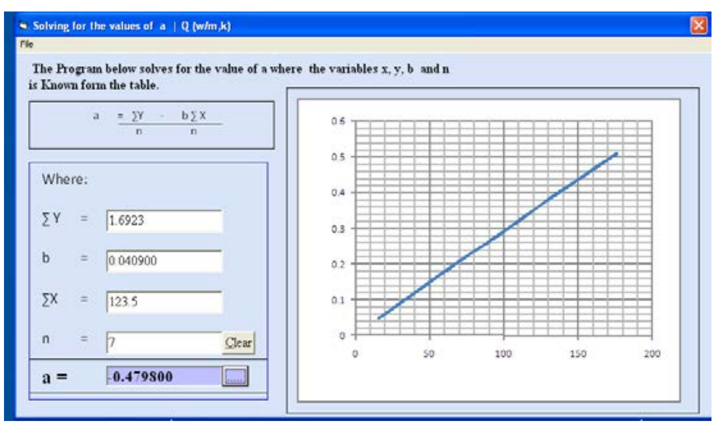


Fig 7: *Program interface for calculating of (a)*

4.1.2 Program Calculation for (b)

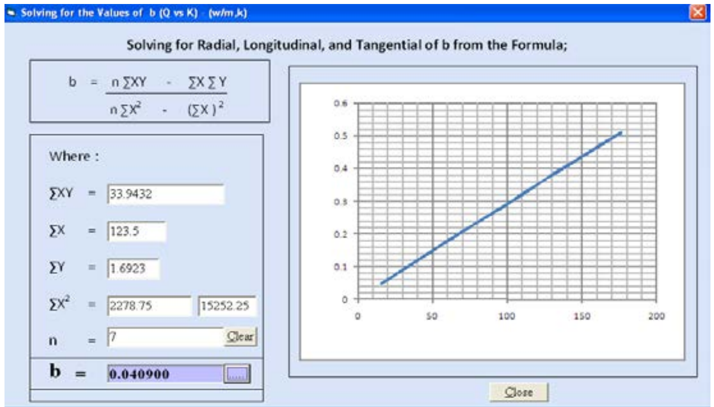


Fig 8 : Program interface for calculating of (b)

4.1.3 Program Calculation for (r)

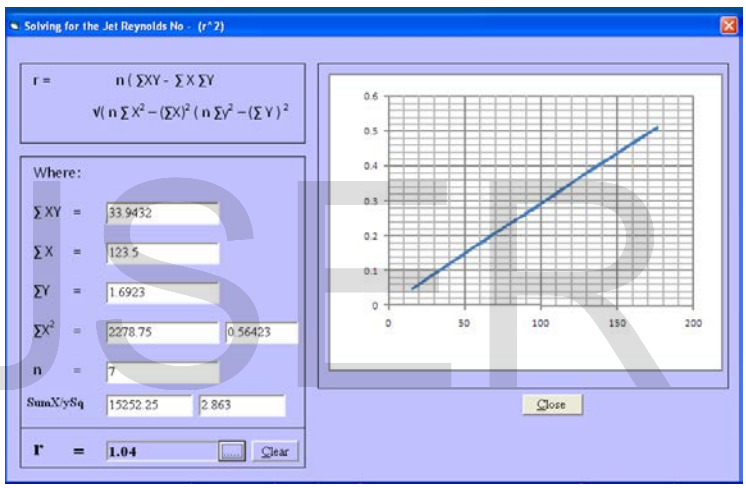


Fig 9 : Program interface for calculating of (r)

5.0 COMPARISONS ON THERMAL CONDUCTIVITIES OF NIGERIAN WOODS

5.1 INVESTIGATION UNDER RADIAL TEST

Table 5.1 of graph figure 10 depicts that the range of *K* of Mahogany is 0.048 to 0.51 w/m^oC, Agba 0.0479 to 0.506 w/m^oC and Melina 0.0476 to 0.502 w/m^oC. It is therefore deduced that Mahogany has highest thermal conductivity followed by Agba, then Melina under radial test.

Table: 5.1: Table of K of the Wood Samples in Radial Direction

S/NO	ΔT (°C)	K - (w/m,°C) - Mahogany	K - (w/m, °C) - AGBA	K - (w/m, °C) - MELINA
1	12	0.048	0.0479	0.0476
2	14	0.0893	0.0891	0.088
3	16	0.166	0.165	0.163
4	18	0.235	0.234	0.232
5	20	0.279	0.278	0.276
6	22	0.368	0.364	0.361
7	24	0.51	0.506	0.502

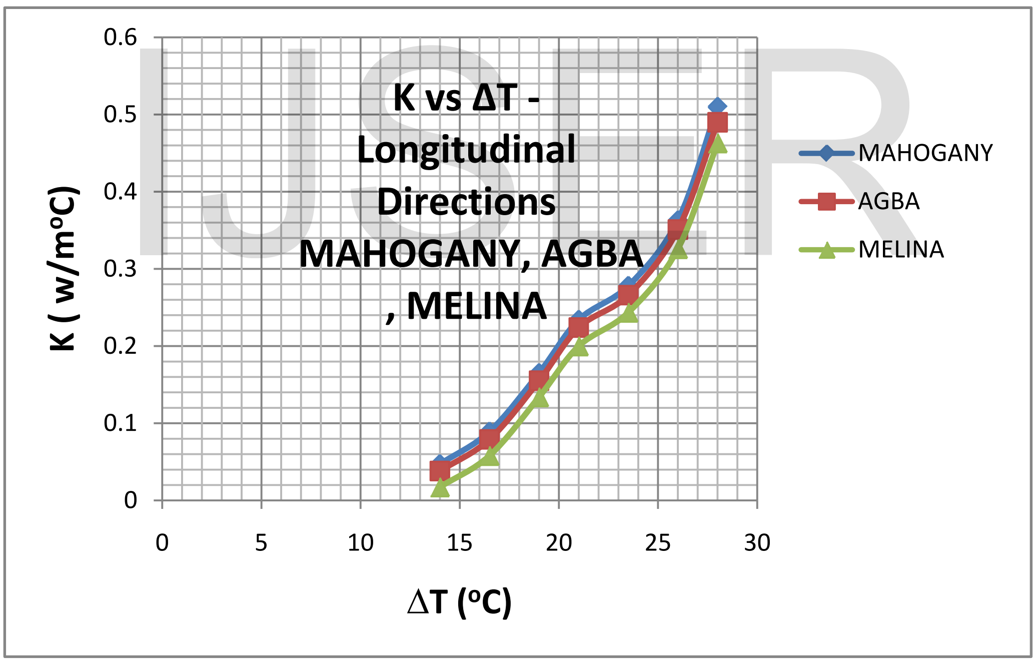


Figure 10: *K vs ΔT radial direction for the three samples*

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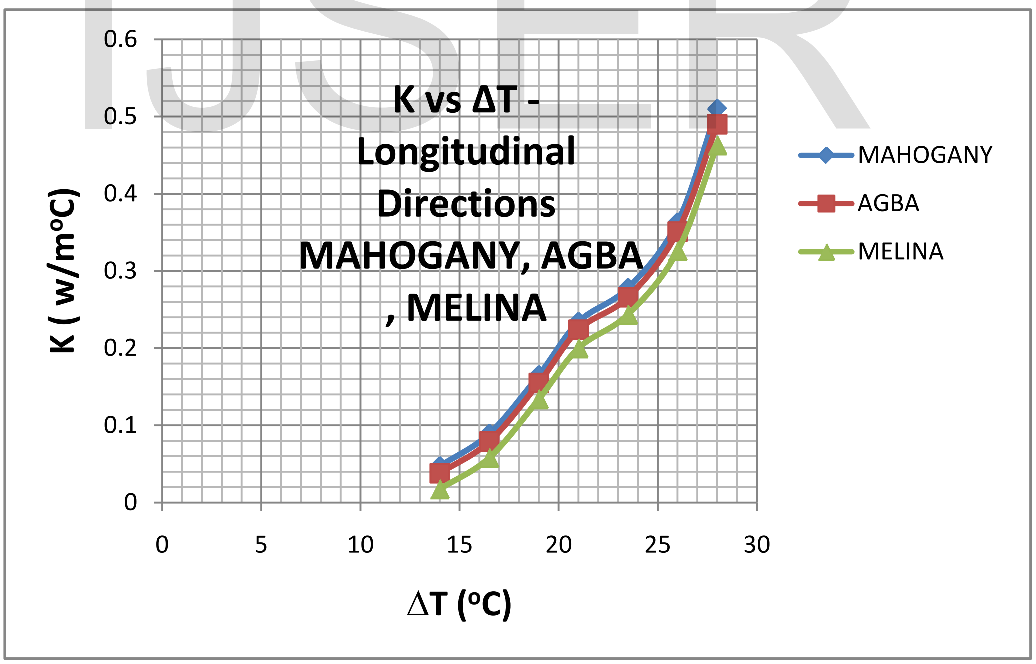
5.2 INVESTIGATION UNDER LONGITUDINAL TEST

Table 5.2 of graph figure 11 shows that the range of *K* of Mahogany is 0.047 to 0.51 *w/m^{o}C*, Agba is 0.046 to 0.50 *w/m^{o}C* while Melina is 0.47 to 0.493 *w/m^{o}C*. This shows that Mahogany has the highest *K* value followed by Agba and Melina under longitudinal test.

Table 5.2 : *K for the Wood Samples in Longitudinal Direction*

S/NO	ΔT (^{o}C))	K - (w/m, ^{o}C) - Mahogany	K - (w/m, ^{o}C) - AGBA	K - (w/m, ^{o}C) - MELINA
1	14	0.047	0.046	0.0474
2	16.5	0.0891	0.089	0.088
3	19	0.165	0.165	0.164
4	21	0.234	0.233	0.230
5	23.5	0.278	0.276	0.2736
6	26	0.363	0.361	0.356
7	28	0.51	0.50	0.493

Figure 11: *K vs dT longitudinal direction for the three samples*



5.3 INVESTIGATION UNDER TANGENTIAL TEST

Table 5.3 of graph figure 12 shows that the range of *K* of Mahogany is 0.048 to 0.51 *w/m^{o}C*, Agba is 0.0476 to 0.496 *w/m^{o}C* while Melina is 0.0479 to 0.505 *w/m^{o}C*. This means that Mahogany also has the highest *K* values followed by Melina then Agba under tangential test.

Table of 5.3: *K for the Wood Sample in Tangential Direction*

S/NO	T (^{o}C)	K - (w/m, ^{o}C) - Mahogany	K - (w/m, ^{o}C)- MELINA	K - (w/m, ^{o}C) - AGBA
1	13	0.048	0.0479	0.0476
2	15	0.0892	0.0891	0.088
3	17	0.166	0.165	0.164
4	19.5	0.235	0.234	0.23
5	21	0.28	0.276	0.274
6	23	0.365	0.361	0.355
7	25	0.51	0.505	0.498

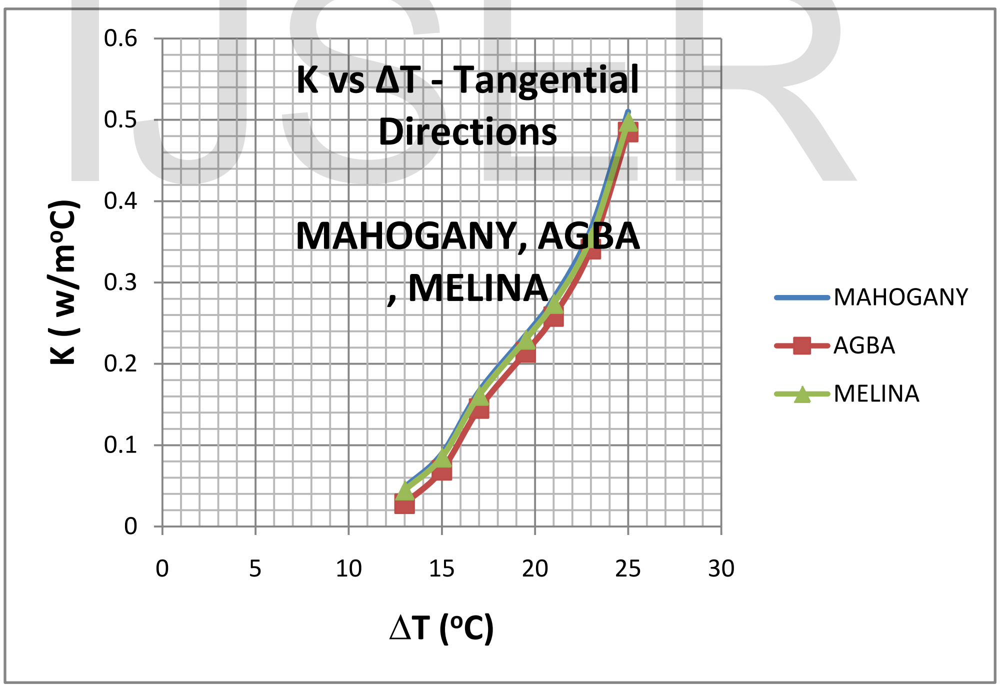


Figure 12: *K vs dT Tangential direction for the three samples*

6.0 CONCLUSION AND RECOMMENDATION

CONCLUSION

After experimental investigation on the three wood samples considering their thermal conductivities the following conclusions were deduced:

- Thermal conductivity of mahogany is highest in radial test with range of *K* - 0.048 to 0.51 w/m^oC, Agba 0.0479 to 0.506 w/m^oC and Melina 0.0476 to 0.502 w/m^oC.
- The thermal conductivity of Mahogany is highest in longitudinal test with range of K - 0.047 to 0.51 w/m^oC, Agba is 0.046 to 0.50 w/m^oC while Melina is 0.47 to 0.493 w/m^oC.
- The thermal conductivity of Mahogany is also highest in tangential test with range of K - 0.048 to 0.51 w/m^oC, Agba is 0.0476 to 0.496 w/m^oC while Melina is 0.0479 to 0.505 w/m^oC
- From the results obtained, it is shown that thermal conductivity of wood is a structure dependent property, which depend on the grain directions of wood in radial, longitudinal and tangential.

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