Experimental Determination of Thermal diffusivity of Teak Wood as a Function of Water Content.

Malahimi ANJORIN, Aristide C. HOUNGAN, Christophe AWANTO, Alain ADOMOU, Antoine VIANOU

Abstract - The wood of teak is much used as building materials in Benin. The quest of comfort conditions in housing needs a better knowledge of thermal performance of the materials forming the walls of building structures. The goal of this study is to estimate the thermal diffusivity of teak as a function of water content using the regular state method. The analysis of the results shows that teak can be used as a good thermal insulating material which allows realizing thermal comfortable apartments in fair conditions.

Keywords: thermal diffusivity, thermal comfort, water content, building materials

◆

1 INTRODUCTION

THE wood lays over a great part of over planet. Actually it represents four hundred millions of ton oil equivalent as energy and gets advantage to be renewable [1]. In Benin forests take up a significant part of the territory and provides among other products some teak which is much used as construction material. The amount of removed wood yearly, can give a valuation about 5.2 millions of ton. More than 90% of that products are used firewood, the remainder as timber and building structures, furnishing and electricity networks pylons [2].

The extensive development of housing trade in Benin and particularly the need to save energy while giving a thermal comfort, require a better knowledge of the thermal characteristics to realize building walls. The use of climate adapted building materials as teak, gives to the building cover, in addition to its insulating rule, to regulate itself temperature and internal hygrometry (via walls inertia and wall breathing phenomena). More over that contributes to minimize the energy consumption of the building. As hygroscopic material, wood is used as a natural regulator of dampness in houses. The goal of the present study is to give an estimation of the thermal diffusiveness of teak as a function of water content using the method of consistent system. This study presents the experimental device and the principle of the method as well as the analysis and the interpretation of results.

2 PRESENTATION OF THE EXPERIMENTAL DEVICE

The method of the thermal regular system imposes the use of an homogeneous thermostatic bath so that the thermoconvective exchange factor (coefficient) is enough higher to get Biot number above 100 [3]. The figure 1 shows the experimental measuring devices. It is composed of a regular metallic vase containing a thermostatic bath with size

540 mm high, 800 mm long and 795 mm wide given an useful volume of 340 l. The vase is put into a box and insolated on the base plate and its lateral sides with polystyrene 90 mm thick.

The heating of fluid in the vase is realized using compact thermostat type LAUDA and serpentine heating at 1 kW / 220V drived by an electronic thermo regulator. The target temperature is set with an electron potentiometer and the reading is made on a digital display dial. The temperature stabilization obtained in time is ± 0.1°C. The water is intensively stired with a helix integrated agitator to the system. Considering the volume of water to boil, a powerful pump 750W/ 220V associated at the same time with the agitator, that allows to distribute regularly the heat flow produced by the serpentine and the thermostat.

The testing sample of the material is placed in the bath containing water with a constant temperature Tf about 50°C. The temperature of the test tube is measured using some J (iron, constantan) type thermocouple lower diameter, 1mm, oversheathed and insulated. Before measuring, all the thermocouples are first tested. The hole receiving the lead is made with an electric drill, diameter about 1mm, then, the couple setting in the central volume of the test tube, the opening is closed with waterproof glue. All those precautions minimize the intrusive effect of the lead. At the end of the measurement, the samples are cut out and the verticality of the lead at the measuring point is controlled a second thermocouple same type is used to record the temperature of thermostatic bath.

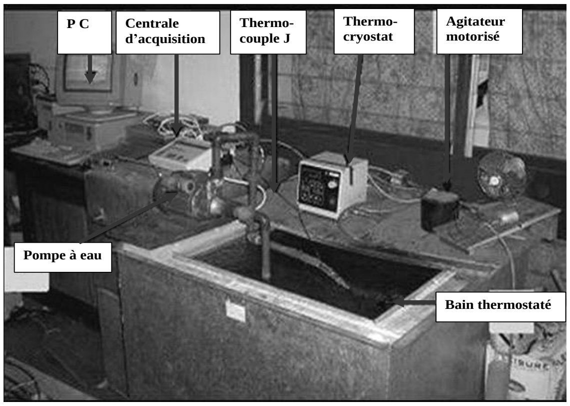

FIGURE1 Measuring device of thermal diffusivity of building materials.

2.1. SAMPLES PREPARATION

In order to measure the thermal diffusivity of building materials for different water contents, small size test tubes are realized to make sure the uniformity of the dampness into their porous media. To obtain the required water contents, samples are placed during many days either into steam room saturated with water air dried or conditioned into climatic wall. The water contents are controlled using twin samples and measuring at the end their anhydrous mass. The figure3 below shows the photo of samples of teak used. The size and the water content of those samples are recorded in table1.

The samples are cut into three perpendicular plans: transverse section perpendicularly to the stem ax- radical section into a plan running the marrow through tangential section into a remote and parallel plan to the stem ax. The three axial (L) radical (R) and tangential (T) directions are the anisotropic directions of wood. In that way the six sides of samples are well trimmed into principal anisotropic plans. That has been possible respecting the disposition of the wood ring and drill. The wood samples also are made waterproof with a varnish layer.

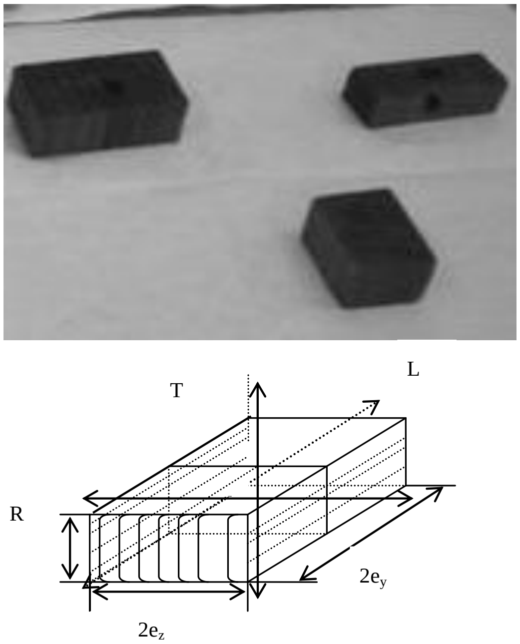

FIGURE 2 : Samples photo**.**

2.2 EQUATION OF TRANSFER INTO MATERIAL

The heat transfer (equation in orthotropic environment as wood is

$$\lambda_x \frac{\partial^2 u}{\partial x^2} + \lambda_y \frac{\partial^2 u}{\partial y^2} + \lambda_z \frac{\partial^2 u}{\partial z^2} - \rho c \frac{\partial u}{\partial t} = 0$$

with $u = T(x,y,z,t) - T_f$ (1)

The figure3 shows the coordinates system for a wood plate.

The initial condition and the Fourier boundaries conditions are :

u (x, y, z, t = 0) = u_0

$$\lambda_x \frac{\partial u}{\partial x} + h_x u = 0 \text{ for } x = \pm e_x \quad (2)$$

$$\lambda_y \frac{\partial u}{\partial y} + h_y u = 0 \text{ for } y = \pm e_y \quad (3)$$

$$\lambda_z \frac{\partial u}{\partial z} + h_z u = 0 \text{ pour } z = \pm e_z \quad (4)$$

Where u_0 = T(x, y, z, t = 0) -T$_f$ T$_f$ surrounding temperature

At the end of essays u (x, y, z, ∞) = 0 The samples temperature tends towards Tf.

Considering the above equations, we can analytically determine at any point of the test tube, the thermal field in variable system. The solution of that problem is obtained bearing on the variables separation method and applying Von Neumann theorem (3). The reduced temperature solution (1) with boundary conditions (2-4) noted

$$\theta = \frac{u}{u_0} = \frac{T(x,y,z,t) - T_f}{T_0 - T_f} \quad (5)$$

is given by

$$\theta = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} A_{ijk} F_{ijk} \exp\left[-\left(n_{ix}^2 F_{ox} + n_{jy}^2 F_{oy} + n_{kz}^2 F_{oz} \right) \right] \quad (6)$$

$n_{i\eta}$ is the positive root of line 1 of transcendental equation

$$\mathrm{cotg}\left(n_{i\eta}\right) = \frac{n_{i\eta}}{\mathrm{Bi}_\eta}$$

with $(\eta = x,\ y,\ z)$

If Biot number. Bi_η tends towards infinity, the suitable numbers have as values ni_η

$n_{1\eta} = \frac{\pi}{2}$, $n_{2\eta} = 3\frac{\pi}{2}$, $n_{3\eta} = 5\frac{\pi}{2}$, $n_{i\eta} = (2i-1)\frac{\pi}{2}$ when the time is superior to that of the regular system starting, the sery (6) becomes convergent and can be replaced accurately better than 1% (3) by its first term:

$$\theta = A_{111} F_{111} \exp(-mt) \quad (7)$$

$$m = \left(\frac{n_{1x}^2 a_x}{e_x^2} + \frac{n_{1y}^2 a_y}{e_y^2} + \frac{n_{1z}^2 a_z}{e_z^2} \right) \quad (8)$$

as linear equation θ in the regular system field, we have:

$$\ln \theta = -mt + Cte \quad (9)$$

The value m can be experimentally obtained by the relation

$$m = \frac{\ln \theta_1 - \ln \theta_2}{t_2 - t_1} = \frac{\ln u_1 - \ln u_2}{t_2 - t_1} \quad (10)$$

In practice, m is used equal to absolute value of the slope line determined by a linear regression from experimental point into regular state. The identification of diffusivity a_x, a_y, a_z needs three experimental recordings on the same type of sample of the material but within characteristic sizes of the test tubes adequately chosen.

For example: in simple case using three test tubes with respective sizes

$$\begin{cases} n°1:\ 2e_x,\ 2e_y,\ 2e_z \\ n°2:\ 2e_x,\ 2e'_y = e_y,\ 2e_z \\ n°3:\ 2e_x,\ 2e_y,\ 2e'_z = e_z \end{cases} \qquad \begin{cases} a_x = 0{,}135\left(5m_1 - m_2 - m_3\right)e_x^2 \\ a_y = 0{,}135\left(m_2 - m_1\right)e_y^2 \\ a_z = 0{,}135\left(m_3 - m_1\right)e_z^2 \end{cases} \qquad (11)$$

Therefore knowing m values representing the variation rate of temperature logarithm during the regular system at any point of each test tube, we can deduce the diffusiveness in comparison with the principal directions by the relation (11).

3. RESULTS AND INTERPRETATION

The identification of the exploitable zone corresponding to regular state needs to define pertinent criteria. Theoritically, the linear regression, concerns only the experimental points corresponding to times defining a Fourier number above 0.23 (3) As Fourier number is a function of the caracteristic size and diffusiveness that values are unknown the time t_r assiociated to the apparition of the regular system can be known exactly. The analysis of the curve f(t) = Ln(ΔT), allows to delimit the exploitable zone with a below limit equal to 1°C so that the measurements not to be dependent on parasites noise and on above limit equal to 22°C of initial difference of the temperature (T_o- T_f) (3). Figure 4 shows the sample temperature variations.

Table1: thermal diffusivity of teak (Tectona Grandis) with 50°C for various water contents to 22% (T_0 - T_F)

Material	Dimensions (mm)	Infra density kg/m³	Water content %	slope s-1	Coefficient of correlation	Diffusivity x10⁻⁷m²/s
Teak (dry)				-0.0135	0.9986	a_L= 5.20 ±0,40
	48.4 x 27.8x 20.8	476.7	0	-0.0142	0.9977	a_R= 1.01 ±0,08
				-0.0173	0.9990	a_T= 0.60 ±0,05
Teak				-0.0091	0.9990	a_L = 2.90 ±0,20
	50.6x 27.1x 21.1	460.4	8.4	-0.0109	0.9971	a_R = 1.50 ±0,10
				-0.0152	0.9994	a_T = 1.60 ±0,10
Teak				-0.0042	0.9960	a_L = 5.70 ±0,50
	49.3 x 28.1x 21.5	510.8	15.6	-0.0039	0.9987	a_R = 1.70 ±0,10
				-0.0025	0.9975	a_T = 0.60 ±0,05
Teak (liquid				-0.0025	0.9930	a_L = 4.00 ±0,30
water)	50.1 x 30.2x 20.1	604.5	22.3	-0.0038	0.9960	a_R = 1.10 ±0,10
				-0.0035	0.9920	a_T = 0.80 ±0,07
Teak (satu-				-0.0059	0.9997	a_L = 1.90 ±0,15
rated)	51.8 x 31.2x 20.1	515.1	123.3	-0.0062	0.9999	a_R = 0.90 ±0,08
				-0.0088	0.9998	a_T = 0.30 ±0,02

In the data processing we have considered pratically the recordings of second half experimental time of acquisition, while taking care to eliminate values of ΔT below 1°C. (Figure 4 et 5).

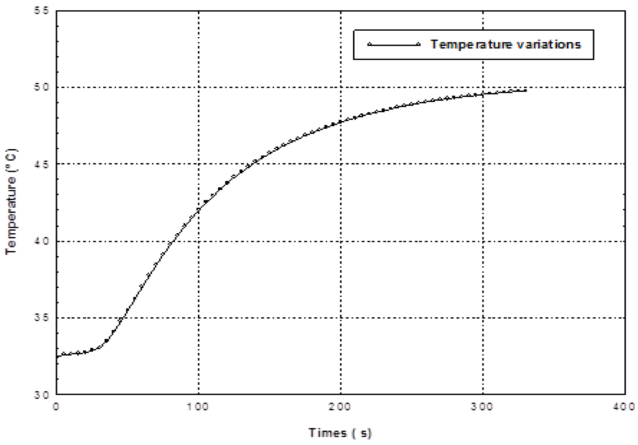

Figure 4. Thermogram (*f(t) = T)* for a dry teak sample (T bath= 50°C)

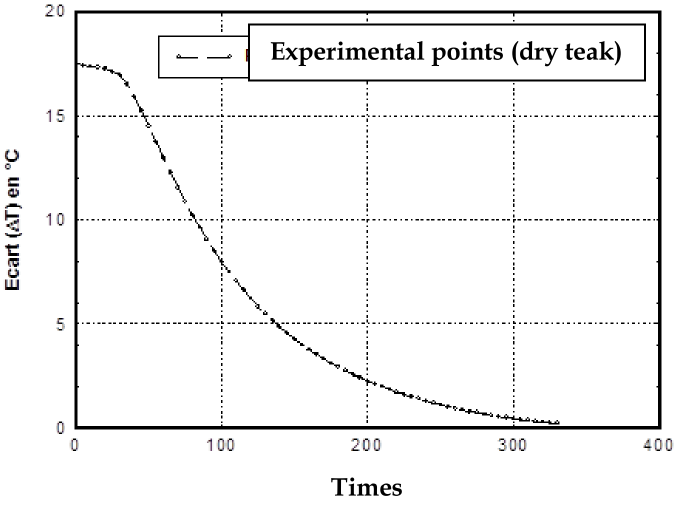

Figure 5. Thermogram (*f(t) = Ln(* ΔT *)*for a dry teak sample (T bath= 50°C)

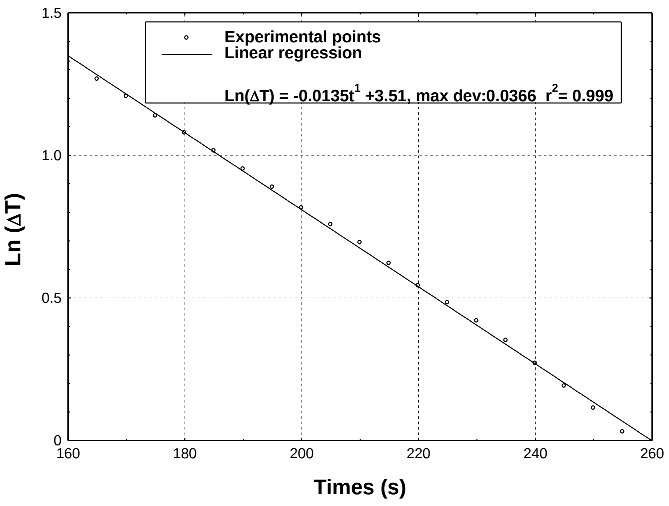

FIGURE 6. linear regression after 160 seconds for dry teak (T bath:= 50°C)

From that table we can deduce an average anisotropic rate varing from a_L/a_R = 1.9-5.2 ; a_L/a_T = 1.8-9.5 ; a_R/a_T = 1.6-3.0. That differences between anisotropic ratio show the influence of water content on the heat transfert. The absolute incertainly values estimated by a trust interval at 95% about the diffusiveness are summarized in table1. The figure 7 representing the longitudinal thermal diffusiveness as function of dampness ratio, shows about teak that longitudinal diffusiveness is higher than transversal one. We notice also on that curves so as transversal (radical and tangential) the thermal diffusiveness is not much over 2.10^{-7} m^2/s. Also for the lower water content (0- 15%) the diffusivity obtained in short cut moves up to maximum. That result has been experimentally proved (4) for water contents between 0 and 10% for wood and other materials.

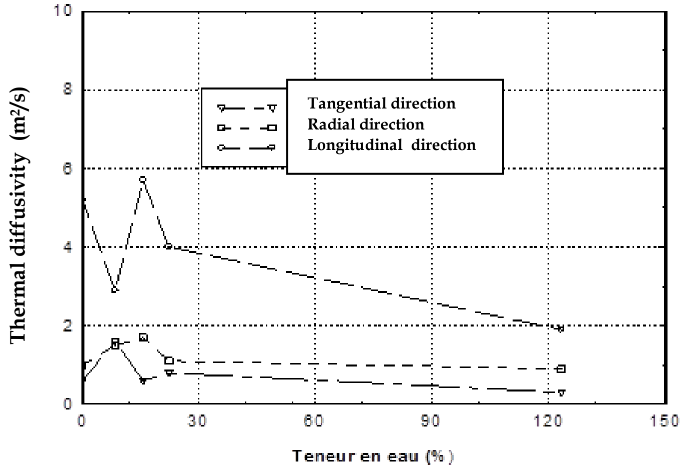

FIGURE 7: Thermal diffusivity of teak as function of water contents

For water contents over 15% we notice a decrease of the thermal diffusivity. That can easily explained if the diffusiveness is interpretated as reducing power of a superficial thermal disturbance within the material. In fact, during the wood humidification, the low water diffusiveness (about 1.44 $10^{-7} m^2/s$ at 20°c) replace the air dry that the diffusivity (about 2.15 $10^{-5} m^2/s$) is very higher than its. Our results are compared with that's of the two air dry woods oils (3). Very used in Benin, what stands out that longitudinal thermal diffusivity is about 3.21 $10^{-7} m^2/s$ for versus 2.49 $10^{-7} m^2/s$ for Swietenia senegalensis Desc when in short cut, these values are 2.69 10^{-7} m^2/s and 1.55 10^{-7} m^2/s respectively. We notice that for a water content of 15,6% our results are lower than that's of those wood oils

4. CONCLUSION

The thermal diffusiveness of teak is measure using the method of regular system. The one advantage of that method is the quick obtainable experimental results (an assay lasts less than 15 minutes). On the other hand, the method of regular system uses a particularly simple device to implement and lend itself well to highly automated measurement. We overall notice the decrease of thermal diffusiveness related to the dampness rate of wood and a greater value of diffusiveness in axial direction compared with transversal one

Nomenclature
e: thickness, m
t: time
x; y, z: space coordinates
u: temperature deviation k
ax ay az : thermal diffusivity depending on x, y, z, $m^2.s^{-1}$
Bi: Biot number
$F_{i,\ j,\ k}$: order function i, j, k
Fo: Fourier number
hx, hy, hz: exchange coefficient depending on x, y, z, $W.m^2.K^{-1}$
n1: appropriate value
T: temperature, °c
m: logarithm variation rate of T during regular system

REFERENCES

[1] A. Houngan, hygrothermic Characterization of local materials of Benin : conductivity and thermal diffusivity, isotherms of sorption and mass diffusivity, Thesis of the National School of the Agricultural engineering of National Forestry. Nancy-France (2008), p 232.

[2] S. Gboyahida, Characterization of the transfers of heat and mass of three tropical Wood gasolines. Memory of Polytechnic D.E.A College of Abomey-Calavi (1997), p.80

[3] A. Vianou, A. Girardey, Exploitation of the regular-state phenomenon in thermokinetics for the determination of the thermal properties of building materials, Publication High-Temperatures- High Press, 25(1993), 635- 641.

[4] D. Quenard, J P. Laurent, H. Sallée - Influence of water content and temperature on the thermal parameters of the plaster Rev. Gen. Therm n°291(1986), 137 – 144.

- **Malahimi Anjorin** received a M.Sc. in Moscow and a Ph.D. degrees in Heat Transfer from INPL of Nancy (FRANCE)
  He is currently Assistant Professor of Heat and Mass transfer, fluid mechanic at Polytechnic School of Abomey-Calavi – University of Abomey-Calavi (BENIN). His principal research interests are applied mechanics and Heat and Mass Transfer in building Material and Biomass energy in Laboratory of Energetics and Mechanics Applied (L.E.M.A)
  e-mail : malahimianjorin1@yahoo.fr

- **Comlan Aristide HOUNGAN** received a M.Sc. in Benin and a Ph.D. degrees in Energetics and Environment from Agro ParisTech /ENGREF of Nancy (FRANCE)
  He is currently Assistant Professor of Heat and Mass transfer, fluid mechanic at the Technological Institute of Lokossa – University of Abomey-Calavi. His principal research interests are applied mechanics and Heat and Mass Transfer in building Material in Laboratory of Energetics and Mechanics Applied (L.E.M.A).
  e-mail : hounaris@yahoo.fr

- **Christophe AWANTO** received a M.Sc. in Paris XII and a a ph.D. Degrees in Energetic from the Université d'Evry Val d'Essonne of France.
  Assistant Professor of Heat and Mass transfer, fluid mechanic at Polytechnic School of Abomey-Calavi – University of Abomey-Calavi (BENIN). –. His principal research interests are applied Energetic in Laboratory of Energetics and Mechanics Applied (L.E.M.A).
  e-mail : christophe.awanto@gmail.com

- **Alain Adomou** received a M.Sc. and a ph.D. degrees in Theoretical Physics from the Russian People University of Moscow, Federation of Russia.
  He is currently Assistant Professor of mechanical theory of continua at the Technological Institute of Lokossa – University of Abomey-calavi. His principal research interests are applied mechanics and theory of gravitation in Laboratory of Energetics and Mechanics Applied (L.E.M.A)
  e-mail : denisadomou@yahoo.fr

- **Antoine VIANOU** received a ph.D. degrees in Heat transfer from the Université d'Evry Val d'Essonne of France.
  He is currently Professor of Heat and mass transfer at Polytechnic School of Abomey-Calavi – University of Abomey-Calavi (BENIN). His principal research interests are applied mechanics and Heat and Mass Transfer in building Material in Laboratory of Energetics and Mechanics Applied (L.E.M.A)
  e-mail:avianou@yahoo.fr