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Research Article

Characterization Phenomena of Thermal Transfer Through an Insulating Material Kapok-plaster Starting from Dynamic Impedance Method

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Abstract: Objective of study is to determine thermal properties of an insulating material from thermal impedance spectroscopy. Plaster used as binder is less than thermal insulating kapok, however thermal characteristics of kapok-plaster material, formed in Semi-conductor laboratory and Solar Energie (UCAD/Senegal), are closer to those of kapok and promotes good thermal insulation. Electrical analogy-Thermal allowed expressing the dynamic thermal impedance of material in dynamic frequency regime. Study of evolution of dynamic impedance starting from representations Nyquist was used to evaluate thermal resistance of material (shunt and serie). A relationship between thermal resistance and thermal conductivity is thus proposed. Influences of exciting frequency and heat transfer coefficient on heat transfer are highlighted.

Keywords: Dynamic impedance, frequency dynamic regime, kapok, nyquist representation

INTRODUCTION

Diversity of building materials (Tamba *et al*., 2007) poses a quality issue in both mechanical strength and the thermal behavior.

Thermal characterization of materials that could be used in construction, optimizes material quantities (Ould Brahim *et al*., 2011a) and to offer a good climate comfort in building.

Wool kapok (Dieng *et al*., 2013) associated with plaster is proposed as insulating useable material in building construction.

Kapok-plaster material used for a simulation study, has the dimensions 27×27×5.2 cm (Ould Brahim *et al*., 2011b); it consists of a homogeneous and isotropic mixture assumed kapok and plaster. Mass of material is 20g with 3.4kg including kapok, a mass rate 58, 8.10^{-2}%. Experimental measurements of thermal conductivity and thermal diffusivity are given respectively values $\lambda = 0.1$ W/m/K and $\alpha = 4{,}73.10^{-7}$ m^2/s (Ould Brahim *et al*., 2011b).

By studying thermal impedance (Boukar *et al*., 2014), considering his behavior limited to low and high pulse, we establish a relationship between electrical and thermal quantities.

THEORY

Study design: Study was conducted in Laboratory of Semi-conductor and Solar Energy UCAD-Senegal.

Figure 1 provides a schematic description of conditions of proposed study. Evolution of temperature module through system is shown schematically for $T_i < T_{02} <\leq T_{01}$. T_{01} and T_{02} are respectively temperature module to external environment interface and internal environment interface.

Mathematical formulation: A the absence of internal heat source, the heat equation boils down to:

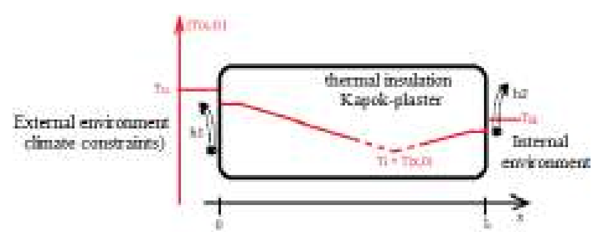

Fig. 1: Diagram of the study device. $T_{01} = T_{02} = 298K$; h_1 and h_2 of the thermal exchange coefficients; Ti = 273K, initial temperature of the material; Lx, length of the material

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$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 \quad (1)$$

The resolution in the frequency dynamic regime of equation system (1) allows obtaining an expression of the temperature of the form (Diallo *et al*., 2014):

$$T(x,\omega,t) = [A_1 \sinh(\beta x) + A_2 \cosh(\beta x)].e^{i\omega t} \quad (2)$$

$$L^* = \frac{1}{\beta} = \sqrt{\frac{\alpha}{2\omega}}(1-i) \quad (3)$$

L* is complex thermal diffusion length. A_1 and A_2 coefficients depend on thermal parameters and boundary conditions Eq. (6) and (7) imposed (Boukar *et al*., 2014, Ould Brahim *et al*., 2011b):

$$A_1 = f(\lambda, \alpha, \omega, h1, h2) \quad (4)$$

$$A_2 = g(\lambda, \alpha, \omega, h1, h2) \quad (5)$$

$$\left\{\lambda \frac{\partial T}{\partial x}\right|_{x=0} = h_1(T(0,t) - T_{01}) \quad (6)$$

$$\left\{-\lambda \frac{\partial T}{\partial x}\right|_{x=Lx} = h_2(T(Lx,t) - T_{02}) \quad (7)$$

At every point of material, the heat flux density (Ould Brahim *et al*., 2011b) through kapok-plaster material is given by Eq. (8):

$$\phi(x,\omega,t) = -\lambda \frac{\partial T}{\partial x} = -\lambda \cdot \beta \cdot [A_1 \cdot \cosh(\beta \cdot x) + A_2 \cdot \sinh(\beta \cdot x)] \cdot e^{i \cdot \omega \cdot t} \quad (8)$$

The dynamic thermal impedance is defined by Eq. (9):

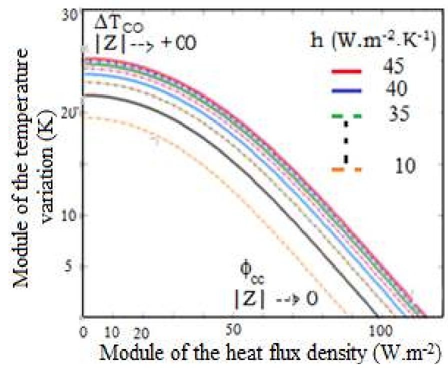
$$Z = \frac{T(x,h1,h2,\lambda,\alpha,t) - T(x=0,h1,h2,\lambda,\alpha,t)}{\phi(x,h1,h2,\lambda,\alpha,t)} \quad (9)$$

RESULTS

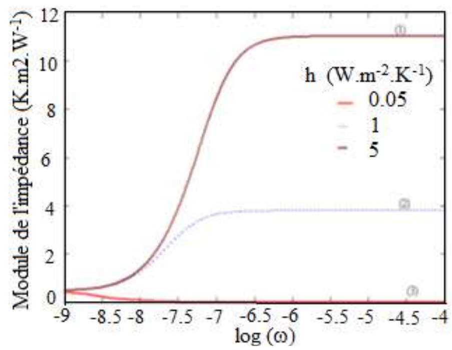
Characteristic T-ϕ: Figure 2a shows evolution of characteristic T-ϕ through material subject to climatic constraints indicated in figure. Influence of heat transfer coefficient is highlighted on impedance:

- Heat flux density $\phi = 0$ corresponds to an open circuit, for a large thickness of material; ΔTco thus corresponds to an infinite impedance.
- ϕ_{cc} is heat flux density penetrating the material by convection to the material surface ($x = 0$).

Dynamic impedance is defined as at any point of the material. Figure 2b shows the evolution of the impedance as a function of the exciting pulse. The boundary of the low pulses the impedance module is independent of heat exchange coefficient; by cons for high pulse, the impedance is an increasing function of the heat exchange coefficient.



(a)



(b)

Fig. 2: (a): Evolution temperature-heat flow density through kapok-plaster material; Influence of heat transfer coefficient; (b): Evolution of thermal impedance module of the material versus the logarithm of excitation pulse; influence of the thermal exchange coefficient at front of material; $h_2 = 0.05 W.m^{-2}/K$

Physical meaning of the limit values of the overall heat transfer coefficient: We define the overall heat transfer coefficient by the equation:

$$K = \frac{1}{|Z|} \quad (10)$$

From various curves obtained on the model in Fig. 2b, we give different values of the overall heat transfer coefficient in Table 1.

For bass pulsations, we have:

$$K \approx \frac{\lambda}{Lx} \quad (11)$$

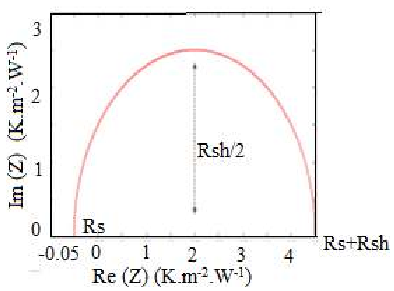
with a relative error of the order of 2%.

Table 1: Comparative table limit values of the overall heat transfer coefficient with the thermal conductivity of the material

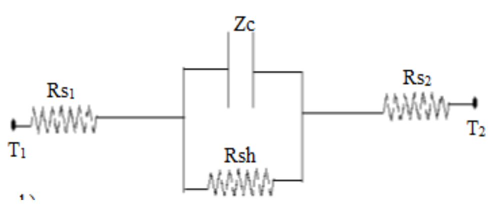
λ/Lx(W.m^{-2}/C)		2	2	2	2	2	2	2	2	2	2	2	2	2	2
h_2 (W.m^{-2}.°C^{-1})		0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
h (W.m^{-2}.°C^{-1})		0.05	1	5	10	20	30	40	50	100	200	500	103	104	105
|Z|(°C.m^2/W)	$\omega\to0$	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
	$\omega\to\infty$	10^{-4}	3.80	11	14.2	16.6	17.6	18.5	19.2	19.6	19.8	19.9	20	20	18.2
K (W.m^2/°C)	$\omega\to0$	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96
	$\omega\to\infty$	10^4	0.26	0.09	0.07	0.06	0.056	0.054	0.052	0.050	0.050	0.050	0.050	0.050	0.055

Table 2: Evolution of electrical and thermal quantities depending on heat exchange coefficient in front face; h_2 = 0.05 W.m^{-2}/°C

h	|Z| (°C.m2/W)		Rs+R_{sh}	[Rs]	R_{sh}	K(W.m^{-2}/°C)		λ/Lx
(W.m^{-2}/°C)	$\omega\to0$	$\omega\to\infty$	(°C.m^2/W)	(°C.m^2/W)	(°C.m^2/W)	$\omega\to0$	$\omega\to\infty$	(W.m^{-2}/°C)
0.05	0.51	10^{-4}	0.5	99.10^{-5}	0.5	1.96	104	2
1	0.51	3.8	0.5	3.8	4.3	1.96	0.26	2
5	0.51	11	0.5	11.04	11.5	1.96	0.09	2
10	0.51	14.2	0.5	14.24	14.72	1.96	0.07	2
20	0.51	16.6	0.5	16.63	17.13	1.96	0.06	2
30	0.51	17.6	0.5	17.71	18.26	1.96	0.06	2
35	0.51	19.9	0.5	18.01	18.59	1.96	0.06	2
40	0.51	18.2	0.5	18.21	18.80	1.96	0.06	2
45	0.51	18.3	0.5	18.35	18.85	1.96	0.05	2
50	0.51	18.5	0.5	18.51	19.01	1.96	0.05	2
100	0.51	19.2	0.5	19.23	19.73	1.96	0.05	2
200	0.51	19.6	0.5	19.61	20.11	1.96	0.05	2
500	0.51	19.8	0.5	19.85	20.35	1.96	0.05	2
1000	0.51	19.9	0.5	19.93	20.42	1.96	0.05	2
10000	0.51	20	0.5	20	20.50	1.96	0.05	2
100000	0.51	20	0.5	20.01	20.51	1.96	0.05	2



(a)



(b)

Fig. 3: (a): Evolution of imaginary part as a function of real part of impedance thermique: h = 0.05 W.m^{-2}/K; h_2 = 0, 05 W.m^{-2}/K; (b): Equivalent circuit model of kapok-plaster material in climate containtes frequency in dynamic regime. Rs = Rs_1+Rs_2; Rs_1 = series resistor to the front face; Rs_2 = series resistance to the back face

Lx : Material thickness
λ : Thermal conductivity kapok-plaster

The influence of the heat exchange coefficient is negligible at low pulses on the conduction phenomena and characterizes the overall heat transfer coefficient.

For high pulse, K tends to the value of the convective heat exchange coefficient for h_1 = h>>h_2.

The low pulsations promote phenomena of conduction through the material and provide access to the thermal conductivity λ, while the high frequencies favoring surface exchange phenomena and possible to obtain the heat transfer coefficient h_2 at of the inner face.

Relationship between electrical and thermal parameters: Figure 3a is a Nyquist representation of the thermal impedance of Kapok-plaster material. It provides series and shunt resistors (Rs, Rsh) translating conduction phenomena through material. Table 2 is obtained by exploiting Nyquist representations corresponding to different climatic stresses under the system.

Figure 3b is an electrical representation of material; Zc is the capacitive impedance of the wall translating the heat storage phenomena for kapok-plaster wall. Table 2 shows that we have:

$$\frac{1}{R_{th}} = \frac{1}{R_s + R_{sh}} = 2W.m^2.°C^{-1} \qquad (12)$$

et

$$\frac{\lambda}{Lx} = 2W.m^2.°C^{-1} \qquad (13)$$

For low pulse, thermal impedance module depends on thermal conductivity.

For high pulse, impedance module depends on heat exchange coefficients.

Where climatic conditions are comparable in two environments, impedance module is virtually zero, a phenomenon likened to a short circuit; by cons if one of coefficients becomes very important with respect to other, thermal impedance will depend on of the smaller heat exchange coefficient for $T_{01} = T_{02.}$

CONCLUSION

Spectroscopic method has allowed determining thermal properties of thermal insulation. The study results allow considering a thermal characterization of materials by measuring dynamic impedance in frequency dynamic regime.

Limit of impedance module for low pulsation will help to determine thermal conductivity, while high pulses will allow obtaining data on heat exchange coefficients.

The electrical-thermal analogy makes it possible to represent different thermal phenomena: heat conduction and heat storage.

NOMENCLATURE

Symbols:

Lx : Material thickness, m
T : Temperature, K
R : Thermal resistance
h_i : Heat transfer coefficient

Latin letters:

ϕ : Flux density, W.m^{-2}
λ : Thermal conductivity, W/m.K
α : Thermal diffusivity, m^2/s
ω : Pulse excitation, rad/s

Indices/exhibitors:

i : 1, 2 externa

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