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Spectroscopic Analysis of Thermal Behaviour of Kapok-Plaster Material in Dynamic Frequency Regime Established

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ABSTRACT

Thermal exchange phenomena between a wall kapok-plaster and its environment are presented. Study electrical equivalent model was used to show different wall behaviors : for lows pulsation, wall behaves's as inductor and resistor in series and opposing the variation of the heat flux density. For high pulsations, material has a capacitive behavior, storing of heat; thermal insulating character is thus considerable. There exists between these two situations a resonant pulsation $\omega_0 \approx 3.16\ 10^{-3}\ rad/s$ for which the wall obtains a pure resistive behavior.

Keywords: Inductance equivalent- equivalent capacity - Thermal Insulation

1. INTRODUCTION

Characterization of thermal insulation [1] presents a major challenge for energy management in habitat and cold rooms. Use of natural materials such as kapok-plaster [2] as part of thermal insulation reduces harmful effects of non-biodegradable materials in environment.

Thermal characterization techniques are numerous ; for example boxes method or hot plate [3], [4] allows to assess thermal conductivity [5] or the heat exchange coefficient [6] to surface of material.

We propose a characterization from study of thermal impedance of material in frequency dynamic regime. We present temperature and density heat flux characteristics and also we determine different behaviors of thermal insulation by capacitive model [7], inductive or resistive in function external excitation pulsation.

2. STUDY DESIGN

2.1. DIAGRAM OF STUDY DEVICE

Material is a wall kapok-plaster whose thickness is of length L=10cm. It is subject to external climatic stresses on both sides : $T_{01} = 313K$and$T_{02} = 288K$. We consider that the heat transfer is unidirectional and perpendicular to the two faces under climatic constraints; the initial temperature of the material is$T_i = 293K$.

The average thermal diffusivity $\alpha = 4.73.10^{-7} m^2.s^{-1}$et la conductivité thermique moyenne$\lambda = 0.1 W.m^{-1}K^{-1}$ [8].

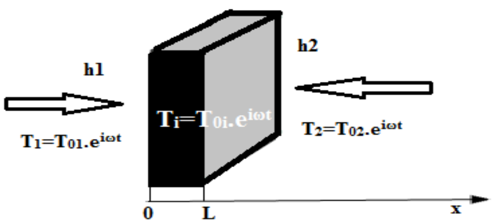

Figure 1: Wall of Kapok-plaster

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2.2. Theory

We propose solution of the heat equation (1) in dynamic frequency regime established for transfer of heat in wall:

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

$$\alpha = \frac{\lambda}{\rho C} \quad (2)$$

Boundary conditions below provide the continuity of heat flux at both sides.

$$\begin{cases} \lambda \dfrac{\partial T(x,t)}{\partial x}\Big|_{x=0} = h_1[T(0,t) - T_{a1}] & (3) \\ \lambda \dfrac{\partial T(x,t)}{\partial x}\Big|_{x=L} = h_2[T_{a2} - T(L,t)] & (4) \\ \mathrm{T}(\mathrm{x},0) = T_i & (5) \end{cases}$$

Equation (6) introduces a variable change for take charge of the initial condition.

$\overline{\mathrm{T}} = \mathrm{T} - \mathrm{Ti}$ (6)

To equation (1) yields equation (7):

$$\frac{\partial^2 \overline{\mathrm{T}}(x,t)}{\partial x^2} - \frac{1}{\alpha}\frac{\partial \overline{\mathrm{T}}(x,t)}{\partial t} = 0 \quad (7)$$

New boundary conditions are given by equations (8), (9) et (10).

$$\begin{cases} \lambda \dfrac{\partial \overline{\mathrm{T}}(x,t)}{\partial x}\Big|_{x=0} = h_1[\overline{\mathrm{T}}(0,t) + Ti - T_{a1}] & (8) \\ \lambda \dfrac{\partial \overline{\mathrm{T}}(x,t)}{\partial x}\Big|_{x=L} = h_2[T_{a2} - \overline{\mathrm{T}}(L,t) - Ti] & (9) \\ \overline{\mathrm{T}}(x,,0) = \mathrm{T}(x,0) - \mathrm{Ti} = 0 & (10) \end{cases}$$

General solution of equation (8) is given by (11).

$$\overline{\mathrm{T}}(x,h_1,h_2,\omega,t) = [A(h_1,h_2,\omega,t)\sinh(\beta.x) + B(h_1,h_2,\omega,t)\cosh(\beta.x)]\exp(i\omega t) \quad (11)$$

Equation (7) yields expression (12) temperature.

$$T(x,h_1,h_2,\omega,t) = [A(x,h_1,h_2,\omega,t).\sinh(\beta.x) + B(x,h_1,h_2,\omega,t).\cosh(\beta.x)].\exp(i\omega t) + Ti \quad (12)$$

Equation (13) gives the heat flux density through the material.

$$\vec{\phi} = -\lambda.\overrightarrow{grad}\ T \quad (13)$$

$$\phi(\mathrm{x},\mathrm{h}_1,\mathrm{h}_2,\omega,\mathrm{t}) = -\lambda\beta.[\mathrm{A}(\mathrm{h}_1,\mathrm{h}_2,\omega,\mathrm{t}).\cosh(\beta.\mathrm{x}) + \mathrm{B}(\mathrm{h}_1,\mathrm{h}_2,\omega,\mathrm{t}).\sinh(\beta.\mathrm{x})].\exp(i\omega.\mathrm{t}) \quad (14)$$

Expressions A1 and A2 coefficients; [2.8] are determined from boundary conditions.
Thermal impedance Z is defined by equation (15):

$$Z = \frac{T(0,t) - T(x,t)}{\phi(x,t)} \qquad (15)$$

3. RESULTS

3.1. Thermoelectric characteristics (ΔT,ϕ)

We represent in Figures 2 and 3 the variation in temperature across the kapok-gypsum material according to the heat flow density. From an electrical point of view, we have different operating point ranging the "short circuit" x = 0 to $\Delta T = 0$, at circuit practically "open" for x = L and $\Delta T = \Delta T_{co}$ reaching a maximum value.

The quality of the insulation is more important than the thickness x to reach the open circuit is low. Figure 1 and Table 1 show that ΔT_{co} increases with the thermal exchange coefficient at the front side therefore with the flux coming from to front face ϕ_c . For fixed thermo physical parameters, the thickness of effective thermal insulation is a function of the heat exchange coefficient.

Figure 2 and Table 2 show the influence of external excitatory pulse on the heat transfer. ΔT_{co} decreases as the pulsation increases which corresponds to relatively low periods of the external climatic stresses. Therefore, for major excitatory pulses, the material thickness is less important.

It should also be noted that the short-circuit impedance corresponds to zero while the open circuit impedance matching "infinity" that is very big. The behavior of the thermal impedance is studied from a spectroscopic study.

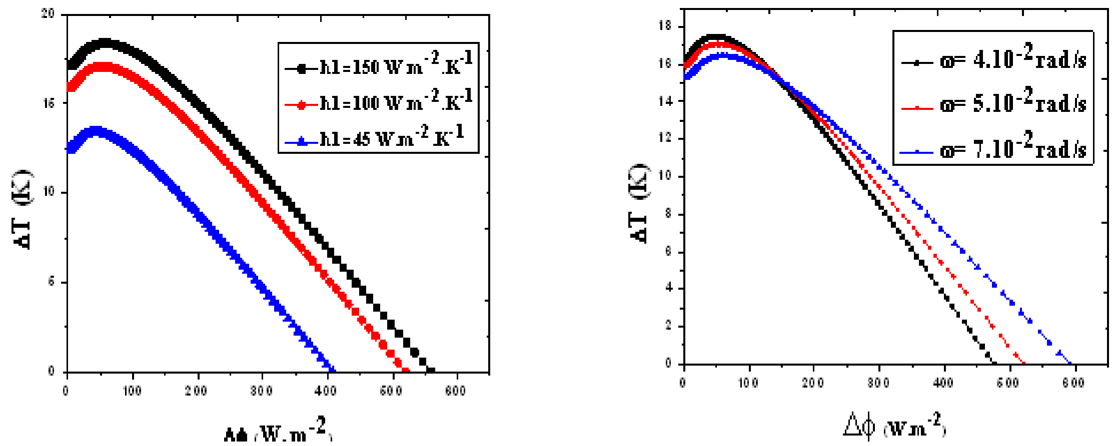

Figure 2: Characteristic temperature - heat flux density (ΔT,ϕ)**:** **(a)** influence of heat transfer coefficient; $\omega = 5.10^{-2}$ rad.s^{-1}; h_2= 5 W.m^{-2}.K^{-1}; **(b)** influence pulsation; h_1= 100 W.m^{-2}.K^{-1}; h_2= 5 W.m^{-2}.K^{-1}.

Table 1: ΔT_{co} and ϕcc Influence of h_1.

h_1 (W.m^{-2}.K^{-1})	150	100	45
ΔT_{co} (°C)	16.96	15.63	12.08
ϕ_{cc} (W/m^2)	559.36	519.61	405

Table 2: ΔT_{co} and ϕ_{cc}. Influence of pulsation

ω (rad.s^{-1})	4.10^{-2}	5.10^{-2}	7.10^{-2}
ΔT_{co} (°C)	16.16	15.55	15.23
ϕ_{cc} (W/m^2)	473.64	519.83	589.67

3.2. Behavior impedance spectroscopy.

A comparative study of results observed at figures 4, 5 and 6 show three different behaviors of material in function of pulsation. For $\omega_0 = 3.16\ 10^{-3}\ rad/s$ the cut-off pulsation corresponding to the maximum impedance (extremum of Figure 4) or Im (Z) = 0 for the Figure 5 and inflection point of Figure 6 corresponding to a zero phase. These figures show that the thermal behavior of the material depends strongly on the exciter pulsation.

a) c Forr $\omega < \omega_0$, impedance module increases with the excitation pulse (Figure 4), reflecting a decrease in the heat flux density through the material. Figures 5 and 6 show that the storage phenomena of heat by inductive effect prevail. Positive part of the phase (Figure 6) shows the existence of a pulsation $\omega_1 \approx 10^{-3} rad.s^{-1}$
to which the imaginary part of the impedance is positive and maximum (Figure 5); The heat transfer may be represented by Figure 7a. We evaluate the equivalent inductance L from the equation (16). Table 3 gives a few values of the equivalent inductance. Thermal inductance reflects opposition to the passage of heat flux in the wall that occurs for low pulsation.

$$L = \frac{\left|\mathrm{Im}(Z)_{\max}\right|}{\omega_1} \qquad (16)$$

Table 3: Values of thermal inductance: ω_1=1.17.10^{-3} rad/s

h (W.m^{-2}.K^{-1})	150	100	45
L (K.m^2.s.W^{-1})	663	646	612

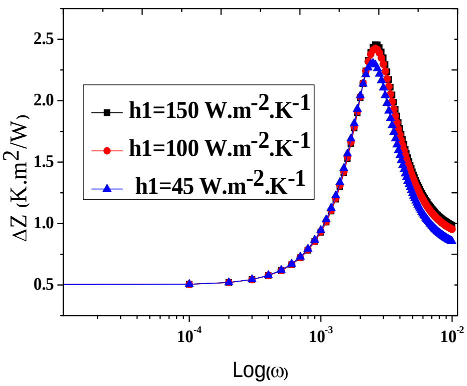

Figure 4 : Module of impedance as a function of excitation pulsation T_{01}=313 K ; Ti=293 K; T_{02}=288 K ; x=0.05m, h_2= 5 W.m^{-2}.K^{-1}

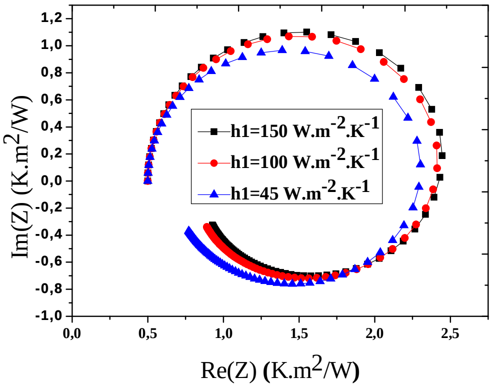

Figure 5 : Module of impedance as a function of excitation pulsation T_{01}=313 K ; Ti=293 K; T_{02}=288 K ; x=0.05m, h_2= 5 W.m^{-2}.K^{-1}.

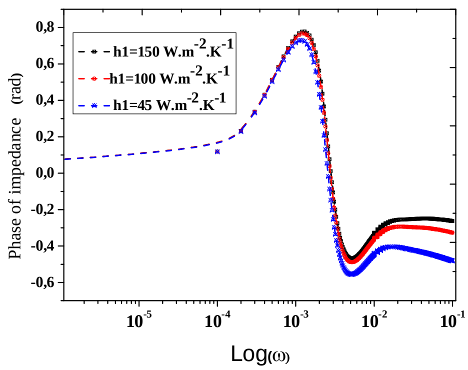

Figure 6 : Phase of impedance as a function of excitation pulse. Influence of heat exchange coefficient. T_{01}=313 K ; Ti=293 K; T_{02}=288 K ; x=0.05m, h_2= 5 W.m^{-2}.K^{-1}.

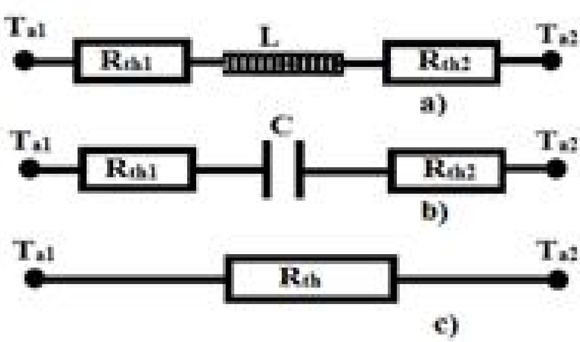

Figure 7: Equivalent electrical circuits

b) For $\omega > \omega_0$: impedance module decreases with excitation pulsation (Figure 4). Figures 5 and 6 show that the phenomena to build up of heat for capacitive effect prevail. Negative part of phase (Figure 6) shows the existence of a pulsation $\omega_2 \approx 4.57.10^{-3} rad.s^{-1}$ to which imaginary part of impedance is negative and minimum (Figure 5); Heat transfer may be represented by Figure 7b. Capacitive effects are sensitive to variation of heat exchange coefficient. We evaluate equivalent capacitance C of material by (17). Table 4 gives some values of equivalent capacity depending on heat transfer coefficient. Equivalent capacity translates storage phenomena of heat by material that occurs at high pulsations.

$$C = \frac{1}{\omega_2 \left| \text{Im}(Z)_{\min} \right|} \qquad (17)$$

Table 4: Capacitance values: $\omega_2 = 4.57.10^{-3}$ rad/s

h (W.m^{-2}.K^{-1})	150	100	45
C (W.s/K.m^2.rad)	486	465	405

c) For $\omega = \omega_0$, impedance module takes a maximum value (Figure 4); effect of excitation pulsation is practically nil for $\omega_0 \approx 5.9.10^{-3} rad.s^{-1}$corresponding to a phase of zero impedance (Figure 6). Imaginary part of impedance is thus zero. Figure 5 allows to evaluate average resistance of material. Electrical model of Figure 7-c represents thermal behavior of material.

Table 5 gives values of series resistance $R_s(\omega \to 0)$, de la résistance shunt R_{sh} (pour $\to \omega_0$, we have $R_s + R_{sh}$). Heat transfer coefficient (Up) for assessing the thermal insulating nature of the material.

Table 5: Values of resistors from Nyquist representation

h$_1$ (W.m^{-2}.K^{-1})	45	100	150
R$_s$ (K.m^2.W^{-1})	0.5	0.5	0.5
R$_{sh}$ (K.m^2.W^{-1})	1.77	1.9	1.93
$R_{th} = R_s + R_{sh}$ (K.m^2.W^{-1})	2.27	2.4	2.43
$U_p = \frac{1}{R_{th}}$(W.m^{-2}.K^{-1})	0.44	0.42	0.41

4.CONCLUSION

Thermal characterization of materials by analyzing thermal impedance allows to highlight different behavior of thermal insulating material. Under external climatic constraints including excitation pulsation or period of external climatic stresses, wall shows capacitive behavior, inductive or resistive. Assessment of these characteristics in the different bands pulsation optimizes use of thermal insulation materials.

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