

Research Article

Changes in Temperature in a Material Kapok-plaster Sample in Dynamic Frequential Regime

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Abstract: We propose in this study, changes in temperature in a kapok-plaster material, depending on the depth, in dynamic frequential regime. The temperature changes are studied for different values of the temperature exciter frequency and the coefficient of convective heat exchange at the front face of the sample. The studies have helped to assess the length of the effective heat insulating layer and to demonstrate the dependence of the quantity of heat exchanged in the material relative to the exciter frequency. The curves show the existence of a frequency below which there is reversal of the effect of the frequency and they show also the existence of a limit value for the temperature when the exchange coefficient on the front face of the sample exceeds the value of 100 W/m²/°C.

Keywords: Coefficient of convective heat exchange, dynamic frequential regime, exciter frequency, temperature

INTRODUCTION

The sample used in this study consists of kapok and plaster and has a parallelepiped shape 27×27×5.2 cm. It has a mass of 3.4 kg, including 20 g of kapok, a mass content of 0.59%. Its thermal conductivity and thermal diffusivity, as determined by the method for boxes have respective values: $\lambda = 0.1$ W/m/K and $a = 4.73 \cdot 10^{-7}$ m²/sec (Voumbo *et al.*, 2010).

We study the temperature variations within the sample when both faces (front and rear) are subjected to external stresses in dynamic frequency regime. Influencing variables are:

- The depth of the material
- Excitation frequency
- Coefficient of convective heat exchange

METHODOLOGY

Study model: The sample is subjected to exciter temperatures on both faces. Figure 1 shows the experimental device.

Heat exchanges happen at relatively moderate temperatures and we neglect the radiative exchanges versus convective exchanges. Thus, in this study, the heat transfers to the outer wall of the sample takes place mainly through the convective heat transfer coefficient (Ould Brahim *et al.*, 2011).

Parameters h_1 and h_2 represent the respectively coefficients of convective heat transfer on the front and on the rear face.

T_{a1} is the temperature in dynamic frequential regime of the fluid constituting the environment in the front face.

T_{a2} is the temperature in dynamic frequential regime of the fluid composing the ambient medium to the rear face.

$T_1 = T(0, t)$ is the temperature of the front face of kapok-plaster material for $x = 0$.

$T_2 = T(L, t)$ is the temperature of the rear face of kapok-plaster material for $x = -L$.

L is the length of material in the direction (Ox), temperatures T_{01} et T_{02} are respectively the maximum amplitudes of temperature imposed to neighborhoods of front face and rear face of the planar material; ω is the exciter frequency of imposed temperature to neighborhoods of each face.

Mathematical theory:

Expression of the temperature in the material: The heat equation in a system to a dimension is given generally by Diouf *et al.* (2013):

$$\lambda \cdot \frac{\partial^2 T}{\partial x^2} + P_p = \rho \cdot C \frac{\partial T}{\partial t} \quad (1)$$

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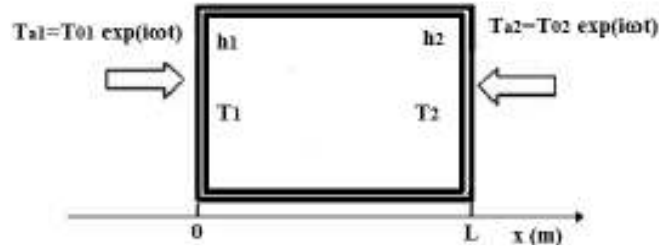


Fig. 1: Planar material subjected to dynamic exciter temperatures in dynamic frequential regime

where,

- λ (W/m/K) = The thermal conductivity of the material
- C (J/kg/K) = The specific heat of the material
- Pp (W/m³) = The heat well
- ρ (kg/m³) = The density of the material
- x (m) = The abscissa along an axis oriented in a direction perpendicular to the plane of the material
- T (°C) = The temperature at a given point

In the absence of internal heat source and heat wells, we have: $Pp = 0$.

The heat equation becomes:

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

with,

$$\alpha = \frac{\lambda}{\rho \cdot C} \quad (3)$$

α is the coefficient of thermal diffusivity.

The boundary conditions are given by the following relationships:

$$\lambda \frac{\partial T}{\partial x}(0) = h_1 [T(0, t) - T_{a_1}] \quad (4)$$

$$-\lambda \frac{\partial T}{\partial x}(L) = h_2 [T(L, t) - T_{a_2}] \quad (5)$$

The solution of Eq. (2) in dynamic frequential regime (Ould cheikh *et al.*, 2013) taking into account the relations (4) and (5) leads to the solution:

$$T(x, \omega, t) = [A_1 \cdot \sinh(\beta \cdot x) + A_2 \cdot \cosh(\beta \cdot x)] \cdot e^{i \cdot \omega \cdot t} \quad (6)$$

with,

$$\beta = \sqrt{\frac{\omega}{2\alpha}} (1 + i) \quad (7)$$

We set:

$$L^* = \frac{1}{\beta} = \sqrt{\frac{\alpha}{2\omega}} (1 - i) \quad (8)$$

L^* is the complex thermal diffusion length.

We obtain the expressions of constants A_1 and A_2 :

$$A_1 = \frac{h_1 \cdot h_2 \cdot T_{0_2} - h_1 \cdot T_{0_1} \cdot [h_2 \cdot \cosh(\beta \cdot L) + \lambda \cdot \beta \cdot \sinh(\beta \cdot L)]}{\lambda \cdot \beta [h_2 \cdot \cosh(\beta \cdot L) + \lambda \cdot \beta \cdot \sinh(\beta \cdot L)] + h_1 \cdot [h_2 \cdot \sinh(\beta \cdot L) + \lambda \cdot \beta \cdot \cosh(\beta \cdot L)]} \quad (9)$$

$$A_2 = \frac{h_2 \cdot \lambda \cdot \beta \cdot T_{0_2} + h_1 \cdot T_{0_1} \cdot [h_2 \cdot \sinh(\beta \cdot L) + \lambda \cdot \beta \cdot \cosh(\beta \cdot L)]}{\lambda \cdot \beta [h_2 \cdot \cosh(\beta \cdot L) + \lambda \cdot \beta \cdot \sinh(\beta \cdot L)] + h_1 \cdot [h_2 \cdot \sinh(\beta \cdot L) + \lambda \cdot \beta \cdot \cosh(\beta \cdot L)]} \quad (10)$$

Expression of the heat flux density in the material:

The heat flux density ϕ , expressed in watts per square meter (W/m²) is given by the following relationships:

$$\phi = \frac{d\Phi}{ds} \quad (11)$$

$$\phi = \frac{1}{s} \cdot \frac{dQ}{dt} \quad (12)$$

Φ = The heat flux which reaches the surface S

Q = The amount of heat that enters the surface S at a given time

ϕ = The heat flux density

Temperature T depends on the location x where it is measured. In the case of the temperature in one direction, we define a function $T(x)$. We can search, for a small change in x , the corresponding change in temperature (dT). This one is written:

$$dT = T(x + dx) - T(x)$$

For an average variation, we write:

$$\frac{dT}{dx} = \frac{T(x + dx) - T(x)}{dx} \quad (13)$$

This is commonly called the temperature gradient.

If we consider that the temperature is a linear function of displacement, then the temperature gradient becomes the average of the temperature variation as a function of displacement: $\frac{\Delta T}{\Delta x}$.

Experimentally, if temperature variations are not too large, we realize locally phenomena of heat conduction by Fourier's law, namely the vector flux density \vec{J} , for an isotropic and homogeneous medium, which is given by the following expression:

$$\vec{J} = -\lambda \overrightarrow{\text{grad}}T \quad (14)$$

where, λ (W/m/K) is called the thermal conductivity of the medium and reflects the ability of the medium to conduct heat.

Thus, the heat flux density in a direction ϕ characterized by a unitary vector \vec{i} is:

$$\phi = \vec{J} \cdot \vec{i} = -\lambda \frac{\partial T}{\partial x} \quad (15)$$

From the expression of the temperature in the material, we obtain:

$$\phi(x, \omega, t) = -\lambda \frac{\partial T}{\partial x} = -\lambda \cdot \beta \cdot [A_1 \cdot \cosh(\beta \cdot x) + A_2 \cdot \sinh(\beta \cdot x)] \cdot e^{i \cdot \omega \cdot t} \quad (16)$$

The expressions of β , A_1 and A_2 are given respectively by the relations (7), (9) and (10).

STUDY OF THE CHANGES IN TEMPERATURE

Change in temperature according to the depth of the material, the influence of the exciter frequency ω :
We study the changes in temperature of the front and rear of the material when they are subjected to climatic stresses. The temperature changes are performed depending on the depth of material for different values

of the frequency and the heat exchange coefficient. They are presented in Fig. 2 and 3.

We note that the curves in Fig. 2 have the same shape and they present an area where they are linear and almost horizontal. In this area of about 1 mm deep, the material is sensitive to the front heat exchange. This material layer is the sensitive area to exterior climatic stresses.

For a depth of material between 2.9 and 23.8 mm, we see a sudden drop in temperature. This is explained by the fact that within the material, the phenomena of heat transfer by conduction is greatly attenuated. This layer corresponds to the minimum layer to obtain good thermal insulation: it is the effective thermal insulation layer (Fig. 3).

The curves also allow demonstrating the dependence of heat transfer within the material relative to the exciter frequency of the external environment temperature.

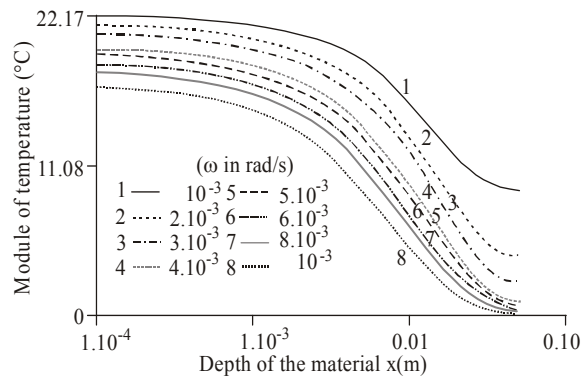


Fig. 2: Variation of the temperature of the module according to the depth of kapok-plaster material, for different values of the exciter frequency $h_1 = 30 \text{ W/m}^2/\text{K}$; $h_2 = 0.05 \text{ W/m}^2/\text{K}$

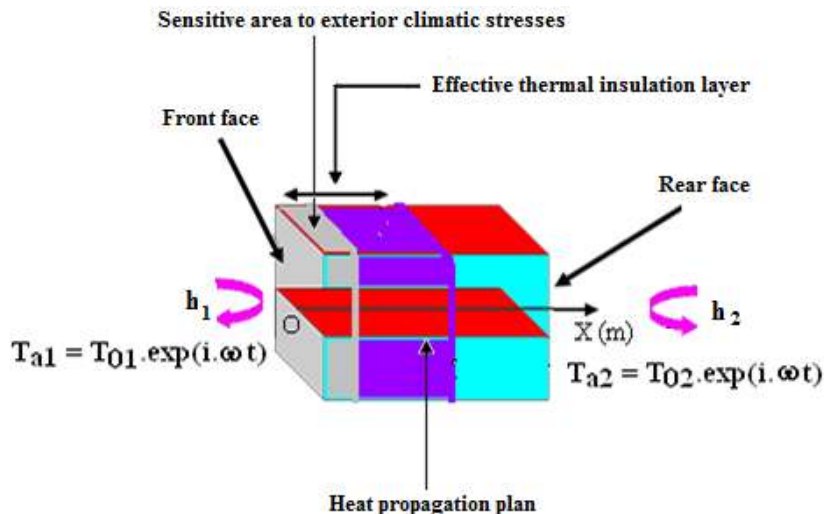


Fig. 3: Diagram of the device of study; viewing of sensitive area to external climate stresses and effective thermal insulation layer

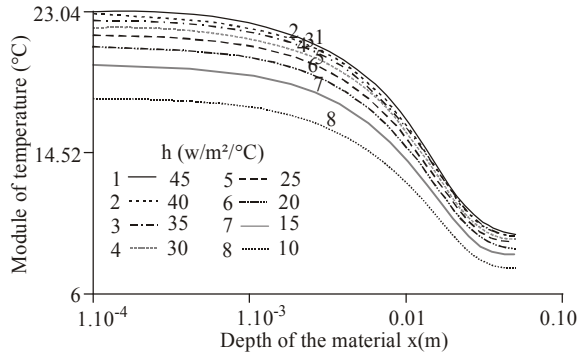


Fig. 4: Variation of the temperature of the module according to the depth of the plaster-kapok material; influence of the convective heat exchange coefficient at front face: $\omega = 10^{-3}$ rad/sec; $h_2 = 0.05$ W/m²/°C

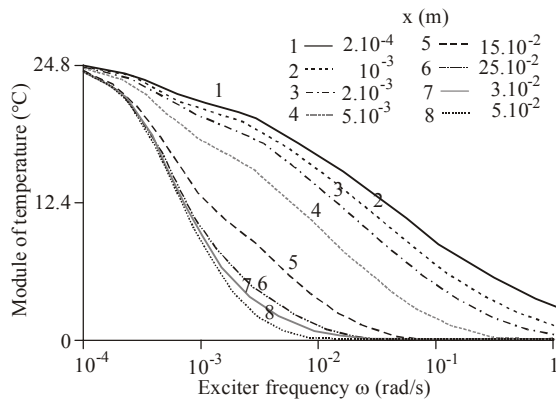


Fig. 5: Variation of the module of the temperature according to the exciter frequency, influence of the depth of the sample, $h_1 = 25$ W/m²/°C; $h_2 = 0.05$ W/m²/°C

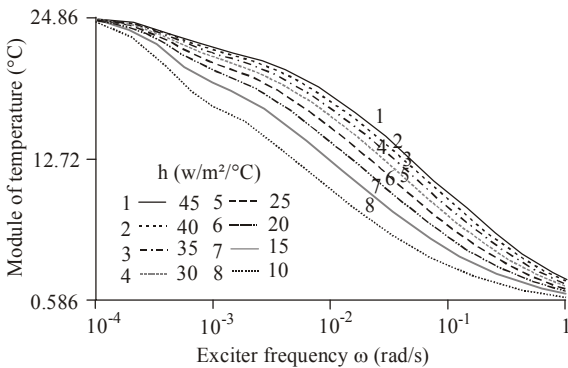


Fig. 6: Change of module of temperature depending of the exciter frequency; influence of heat exchange coefficient, $x = 10^{-3}$ m; $h_2 = 0.05$ W/m²/°C

We note that for a position $x = 0$, to the front face of the material, the greater value of the modulus of the temperature is obtained when the exciter frequency is the lowest. We can say that the quantity of heat exchanged and absorbed by the material is more important when the excitation frequency is low.

This observation is justified by the following equation: $Q = m.c. \Delta T$ wherein Q is the quantity of heat absorbed by the mass m of the material T for a ΔT variation temperature.

When exciter frequency becomes large, the temperature module of the material at the front face where $x = 0$, decreases. The effective thermal insulation layer also becomes smaller.

Note that the curve of temperature (8) which corresponds to an exciter frequency of 10^{-2} rad/sec is above the temperature curve (7) corresponding to exciter frequency of 8.10^{-3} rad/sec. Frequency of 8.10^{-3} rad/sec is the minimum frequency from which we observe reversal of the effect of the exciter frequency.

However, the heat exchange is especially favorable for small values of the exciter frequency.

Change in temperature according to the depth of material, influence of heat transfer coefficient h_1 at front face: Figure 4 shows the influence of the thermal exchange coefficient on the behavior of the temperature within the kapok-plaster material. The curves show the same profile as that of Fig. 2. The effective thermal insulation layer can be estimated to about 2 cm.

The module of the temperature at the front face where there is heat exchange is even higher that the convective heat transfer coefficient is important, unlike the case of the frequency. This physical phenomenon shows that it is important to control the environmental parameters related to the convective heat transfer coefficient such as the speed of movement of the fluid in contact with the material, the nature of the contact surface, the change in temperature of the fluid constituting the environment.

Changes in temperature depending on the exciter frequency at a point of the sample: Figure 5 and 6 show the temperature of the module depending on the exciter frequency within the sample.

Figure 5 shows two categories of curves: the curves (1), (2), (3) and (4) have approximately the same shape and refer to a layer whose thickness is less than or equal to 5 mm; this thickness is much lower than that of the effective thermal insulation layer (about 2 cm).

We also notice that for these curves, the module of the temperature is higher for lower values of the exciter frequency, corresponding to a significant heat absorption by the sample. For exciter frequencies around 10^{-3} rad/sec, the curves show a small variation of the module of the temperature. This frequency band corresponds to a small absorption of heat through the sample. Beyond this frequency band, the module of the temperature decreases rapidly with the frequency and tends to zero when the exciter frequency becomes important. The amount of heat absorbed by the sample decreases when the exciter frequency becomes large whatever the depth, resulting in a decrease of temperature.

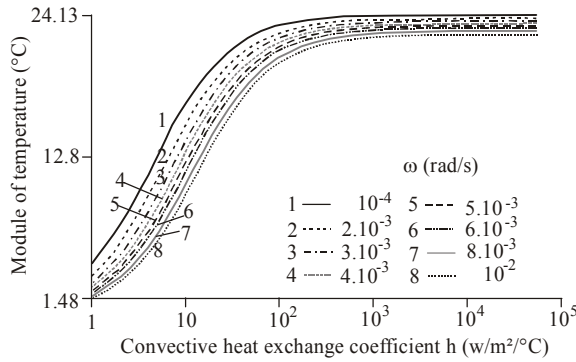


Fig. 7: Variation of the module of temperature depending of the heat exchange coefficient; influence of the exciter frequency, $x = 10^{-3}$ m/°C; $h_2 = 0.05$ W/m²/°C

The second group of curves is formed by the curves (5), (6), (7) and (8). These have the same appearance and refer to a layer of a thickness greater than or equal to the effective thermal insulation layer. The phenomenon of heat transfer by conduction is low in this area. The material has a thermal insulating behavior.

If we look at the evolution of each of these curves, the amount of absorbed heat is large for small values of exciter frequency; it results in a high temperature of the sample to the different positions considered. Near the frequency of 10⁻³ rad/sec (corresponding to an experimental period of about 2 h), we observe a sharp drop in temperature, that is to say a low heat absorption by sample. Beyond this frequency, the module of the temperature decreases rapidly to become very low.

Figure 6 shows the change of temperature inside the sample depending on the exciter frequency, for fixed values of the h_1 heat exchange coefficient.

We consider the position $x = 10^{-3}$ m belonging to the area undergoing strongly influences of the heat exchange at the sample surface to better show the influence of the heat exchange coefficient. The curves of this figure have approximately the same profile. For low values of the exciter frequency (experimental period tends to infinity), the temperature of the sensitive zone to climatic conditions at the sample surface ($x < 10^{-3}$) is large and tends towards the value of the temperature of the fluid constituting the environment. This phenomenon corresponds to a significant amount of heat exchange at the surface of the sample.

The curves generally decrease with the exciter frequency at a given point of the sample and the phenomenon of absorption of heat becomes low when the exciter frequency becomes important. This results in a significant decrease in temperature at this point of the sample.

For exciter frequencies around 10⁻³ rad/sec, we observe a small change in temperature depending on frequency (the curves are almost horizontal). This

frequency band corresponds to optimum frequencies of heat transfer into the sample. Beyond this frequency, the sample absorbs less heat from relatively high frequencies, considering the drop of the temperature module.

The comparison of the series of curves shows that the amounts of heat exchanged in the surface of the sample and absorbed by the sample increases with the heat transfer coefficient. The influence of the heat transfer coefficient is not sufficient in itself to explain the increase in the amount of heat. In effect, the heat exchange coefficient is itself dynamic, depends on the exciter frequency of the temperature of fluid constituting the ambient.

Change in temperature depending on the heat exchange coefficient: To study the variation of temperature as a function of the heat exchange coefficient (Fig. 7), we consider a position $x = 10^{-3}$ m in the sample, in the sensitive zone to climate stresses in the front face of the sample. We vary the temperature according to the thermal exchange coefficient for different values of the exciter frequency.

The curves have the same allure. The module of temperature is low when the value of heat exchange coefficient is small, which corresponds to weak heat transfer between the fluid and the front face of the material.

When the value of heat exchange coefficient becomes large, the module of temperature increases. This phenomenon is due to favorable conditions for great heat absorption by the material, which results in a temperature raise in the vicinity of the heat exchange wall.

For values of heat exchange coefficient greater than 100 W/m²/°C, the module of temperature approaches a limit value close to that of the temperature of the fluid in contact with the wall (front face) of the sample. The sample has stored maximum energy. The temperature of the sample becomes independent of the variation of the heat exchange coefficient.

If we compare the sets of curves in Fig. 7, we find that the temperature of the sample is closely related to the value of the exciter frequency. Low exciter frequencies are favorable to a large heat exchange at the sample wall. Thus, the amount of heat exchanged decreases when the exciting frequency is increased. We can explain this behavior by the phenomena of relaxations that is to say the sample does not have the time to absorb the amount of heat received at a given time before another wave of quantity of heat arises.

The curves of Fig. 8 show the influence of the depth on the evolution of the module of temperature when heat exchange coefficients change.

If we consider one of these curves, the module of the temperature increases with the heat transfer coefficient to reach a maximum value when the heat

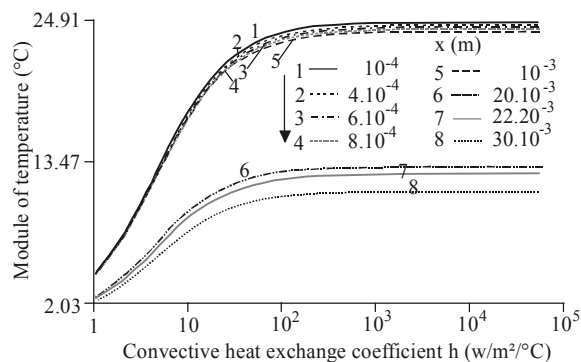


Fig. 8: Variation of module of temperature depending of the heat exchange coefficient; influence of depth, $\omega = 10^{-3}$ rad/sec; $h_2 = 0.05$ W/m²/°C

exchange coefficients are greater than 100 W/m²/°C. The sample has stored the maximum of heat and then causes a break of heat exchanges.

Comparing the curves of Fig. 8 between them, we can see that the modulus of temperature decreases with increasing depth. In the sensitive band with influences of external climatic conditions, $x < 10^{-3}$ m, the variation of this module, based on depth, is low (curves (1) to (5)); by cons, in the effective thermal insulation layer, the module of temperature of the sample is much lower despite the high values of heat exchange coefficients. In this area, the influence of heat exchange on the outside of the sample is negligible and the heat transfer is done by conduction. Given the relatively low value of the conductivity of the sample, the amounts of heat received by the positions beyond the heat insulating layer is low, which results in a low temperature rise of the sample.

CONCLUSION

Figure 2 and 4 permitted to assess the effective thermal insulation layer of the sample to about 2 cm. The curves obtained have also allowed demonstrating the influences of the exciter frequency and the heat transfer coefficient on the heat transfer inside the sample. In addition to the intrinsic parameters such as the thermal conductivity and thermal diffusivity, it must be taken into account the exciter frequency that occurs in the heat transfer within the materials.

By studying the module of temperature as a function of exciter frequency (Fig. 5 and 6) we find that the temperature decreases as the excitation frequency increases, for a given depth and a given convective heat exchange coefficient.

The representations of the module of temperature depending on convective heat exchange coefficient for the determined values of the depth or of the exciter frequency (Fig. 7 and 8) show that, when the exchange coefficient h_1 exceeds 100 W/m²/°C value, the temperature inside the sample approaches a limit value close to that of the fluid in contact with the wall (front face) of the sample. This is explained by the fact that the sample having stored a maximum energy, its temperature becomes independent of the variation of the heat exchange coefficient.

NOMENCLATURE

- C : Specific heat of the material (J/kg/K)
- h_1 : Coefficient of heat transfer to the front face (W/m²/K)
- h_2 : Coefficient of heat transfer to the rear face (W/m²/K)
- L : Length of the material in the direction (ox)
- T : Temperature in K
- ω : Angular frequency (rad/sec)
- λ : Thermal conductivity (W/m/K)
- α : Coefficient of thermal diffusivity (m²/sec)
- Φ : Heat flux (W)
- ϕ : Heat flux density (W/m²)
- ρ : Density of material (kg/m³)

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