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RESEARCH ARTICLE

STUDY IN TRANSIENT REGIME BY ANALYTICAL METHOD OF THERMAL TRANSFER THROUGH AN INSULATING MATERIAL BASED ON TYPHA AND TWO-DIMENSIONAL (2D) CLAY: INFLUENCE OF THE THERMAL EXCHANGE COEFFICIENT ON THE FRONT FACE

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Abstract

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In this study, we propose an analytical method of heat transfer for the determination of temperature and heat flux density of a typha-clay material. The expression for the temperature and the heat flux density are obtained from the resolution of the heat equation. The influences of the exchange coefficient at the front face and of the depth in the material are highlighted in the transient dynamic regime in two dimensions.

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Introduction:-

The misuse of energy **[1]** due to the significant energy demand for industry and domestics has disastrous consequences on climatic conditions **[2]** of planet earth **[3].** Reducing energy consumption in buildings is a major challenge. Indeed, the construction materials of habitats in tropical countries pose a problem of energy efficiency[**4].** Their thermal insulation will not only reduce the energy bill but will also contribute to improving thermal comfort. Several materials are proposed in the field of thermal insulation, these materials can be of synthetic origin (polystyrene, polyurethane, etc.) **[5,6]** or natural (vegetable, animal, mineral) **[7,8].** Methods for characterizing local materials of plant origin are proposed in frequency modulation **[9-11]** or in transient dynamics **[12,13].** For building energy efficiency, we offer a thermal insulation material **[14,15]** based on compressed typha-clay. We consider that the different faces in contact with the external and internal environments are subjected to climatic stresses modeled in transient regime **[16,17].** The influence of the heat exchange coefficient on the front face and of the depth on the interfaces of the typha-clay panel are proposed.

Study model

Study device

The fiber-plaster material is assumed to be homogeneous and of parallelepipedal shape. The depth of the material isL=0,05m; the initial temperature of the material Ti=10^0Cand that of the external ambient environmentsTa1=Ta2=30^0C. The heat exchange coefficients at the front and at the rear are respectively h1and h2. The average thermal diffusivity is α and the thermal conductivity is λ.

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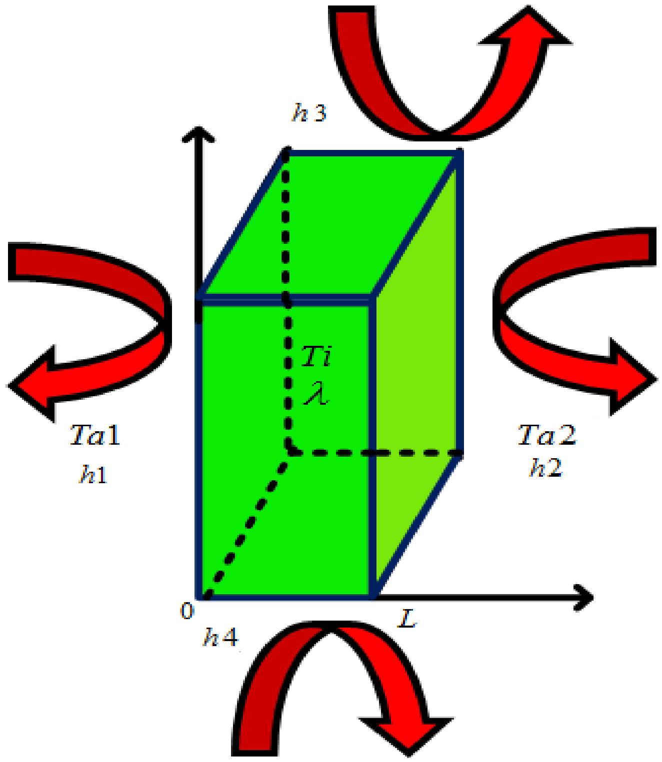

Figure 1:- Study model.

Theory:

The unidirectional heat transfer in the yarn-plaster thermal insulation is governed by equation (1) below:

$$\frac{\partial^2 T(x,y,h_1,h_2,h_3,h_4,t)}{\partial x^2}+\frac{\partial^2 T(x,y,h_1,h_2,h_3,h_4,t)}{\partial y^2}-\frac{1}{\alpha}\frac{\partial T(x,y,h_1,h_2,h_3,h_4,t)}{\partial t}=0;(1)$$

$T=T(x,y,h_1,h_2,h_3,h_4,t)$ is the temperature inside the material; x the depth and t the time. Equation (2) gives the expression of the diffusivity α.

$$\alpha=\frac{\lambda}{\rho c};(2)$$

α is the coefficient of thermal diffusivity ($m^2.s^{-1}$)

λ is the thermal conductivity ($W.m^{-2}.c^{-1}$)

ρ is the density of the material ($kg.m^{-2}$)

Boundary conditions

$$\begin{cases}\lambda\left.\frac{\partial T(x,y,h_1,h_2,h_3,h_4,t)}{\partial x}\right|_{x\equiv 0}=h_1\left[T(0,y,t)-T_a\right];(3)\\ \lambda\left.\frac{\partial T(x,y,h_1,h_2,h_3,h_4,t)}{\partial x}\right|_{x\equiv L}=-h_2\left[T(L,y,t)-T_a\right];(4)\\ \lambda\left.\frac{\partial T(x,y,h_1,h_2,h_3,h_4,t)}{\partial y}\right|_{y\equiv 0}=h_3\left[T(x,0,t)-T_a\right];(5)\\ \lambda\left.\frac{\partial T(x,y,h_1,h_2,h_3,h_4,t)}{\partial y}\right|_{y\equiv L}=-h_4\left[T(x,L,t)-T_a\right];(6)\\ T(x,y,h_1,h_2,h_3,h_4,t=0)=T_i;(7)\end{cases}$$

Dimensionless heat equation

$$\theta(u,v,\tau)=\frac{T(x,y,t)-T_a}{T_i-T_a};(8)$$

with $\theta(u,v,\tau)$: reduced temperature;

$u=\frac{x}{L}$; is a space reduced variable

$v=\frac{y}{L}$; is a space reduced variable

and $\tau=\frac{\alpha t}{L^2}=F_0$

F_0 : Reduced time variable or Fourier number

The heat equation (1) becomes:

$$\frac{\partial^2\theta(u,v,\tau)}{\partial u^2}+\frac{\partial^2\theta(u,v,\tau)}{\partial v^2}=\frac{\partial\theta(u,v,\tau)}{\partial\tau};(9)$$

The boundary conditions (3), (4), (5) and (6) become (10), (11), (12) and (13):

$$\begin{cases}\left.\frac{\partial\theta(u,v)}{\partial\tau}\right|_{u=0}=\frac{h_{1x.}L}{\lambda}\theta(0,\tau);(10)\\ \left.\frac{\partial\theta(u,v)}{\partial\tau}\right|_{u=1}=-\frac{h_{2x.}L}{\lambda}\theta(1,\tau);(11)\\ \left.\frac{\partial\theta(u,v)}{\partial\tau}\right|_{u=0}=\frac{h_{1y.}L}{\lambda}\theta(0,\tau);(12)\\ \left.\frac{\partial\theta(u,v)}{\partial\tau}\right|_{u=1}=\frac{h_{2y.}L}{\lambda}\theta(1,\tau);(13)\end{cases}$$

Let us find the solution of equation (9) in the form of reduced variables separable in space and time given by relation (14):

$$\theta(u,v,\tau)=U(u)V(v)W(\tau);(14)$$

Using the relations (9) and (14) we obtain that of (15)

$$\frac{1}{U(u)}\frac{\partial^2U(u)}{\partial u}+\frac{1}{V(v)}\frac{\partial^2V(v)}{\partial v}+\frac{1}{W(\tau)}\frac{\partial W(\tau)}{\partial\tau}=-\gamma^2;(15)$$

γ is a positive constant.

From relation (15) we obtain two differential equations:

- The differential equation in time is given by (16):

$$\frac{1}{W(\tau)}\frac{\partial W(\tau)}{\partial\tau}=-\gamma^2;(16)$$

- The differential equation in space (17) is written:

$$\frac{1}{U(u)}\frac{\partial^2U(u)}{\partial u}=-\beta^2;(17)$$

The boundary conditions space:

$$\begin{cases} \left.\dfrac{\partial\theta(0,\tau)}{\partial\tau}\right|_{u=0} = B_{i1x}\theta(0,\tau); (18) \\ \left.\dfrac{\partial\theta(1,\tau)}{\partial\tau}\right|_{u=1} = -B_{i2x}\theta(1,\tau); (19) \\ \left.\dfrac{\partial\theta(0,\tau)}{\partial\tau}\right|_{u=0} = B_{i1y}\theta(0,\tau); (20) \\ \left.\dfrac{\partial\theta(1,\tau)}{\partial\tau}\right|_{u=1} = -B_{i2y}\theta(1,\tau); (21) \end{cases}$$

Avec $B_{i1x} = \dfrac{h_{1x}.L}{\lambda}$; $B_{i2x} = \dfrac{h_{2x}.L}{\lambda}$; $B_{i1y} = \dfrac{h_{1y}.L}{\lambda}$ et $B_{i2y} = \dfrac{h_{2y}.L}{\lambda}$

respectively the Biot numbers on the front face and on the back face.
The general solution of the reduced temperature is in the form

$$\theta(u,v,\tau) = \sum_n \left[\left(a_n \cos(\beta_n u) + b_n \sin(\beta_n u)\right)\right]\left[c_n \cos(\mu_n v) + d_n \sin(\mu_n v)\right]e^{-\gamma^2\tau}; (22)$$

$$\begin{cases} \beta_n b_n = B_{i1x} a_n; (23) \\ -\beta_n a_n \sin(\beta_n L) + \beta_n b_n \cos(\beta_n L) = -B_{i2x}\left(a_n \cos(\beta_n L) + b_n \sin(\beta_n L)\right); (24) \end{cases}$$

$$\sin(\beta_n L)(a_n\beta_n - B_{i2x}b_n) = \cos(\beta_n L)(b_n\beta_n + B_{i2x}a_n); (25)$$

$$\tan(\beta_n L) = \frac{b_n\beta_n + B_{i2x}a_n}{a_n\beta_n - B_{i2x}b_n}; (26)$$

The following transcendent equation x:

$$\tan(\beta_n L) = \frac{\dfrac{h_{1x}L}{\lambda}\beta_n + \dfrac{h_{2x}L}{\lambda}\beta_n}{\beta_n^2 - \dfrac{h_{1x}h_{2x}L}{\lambda^2}}; (27)$$

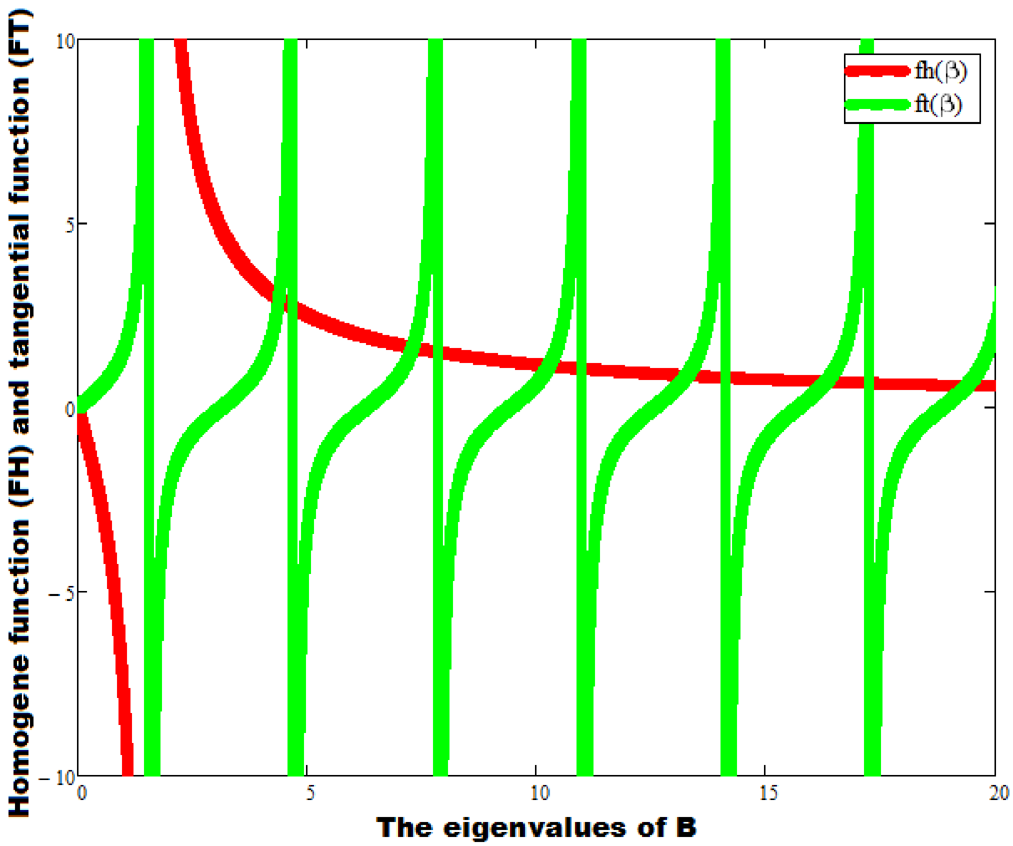

Figure 2:- Curve of the following transcendent equation.

The intersection of the two curves fh (β_n) and ft (β_n) corresponds to the solution.
Table 1 summarizes the eigenvalues found of β_n

Table 1:- The eigenvalues β_n the equation.

n	1	2	3	4	5
β_n	4,5	7,5	10,4	13,4	16,5

Transcendent equation following y

$$\begin{cases} \mu_n d_n = B_{i1y} c_n ;(28) \\ -\mu_n c_n \sin(\mu_n L) + \mu_n d_n \cos(\mu_n L) = -B_{i2y}\left(c_n \cos(\mu_n L) + d_n \sin(\mu_n L)\right);(29) \end{cases}$$

$$\sin(\mu_n L)(c_n \mu_n - B_{i2y} d_n) = \cos(\mu_n L)(c_n \mu_n + B_{i2y} c_n);(30)$$

$$\tan(\mu_n L) = \frac{d_n \mu_n + B_{i2y} c_n}{c_n \mu_n - B_{i2y} d_n};(31)$$

$$\tan(\mu_n L) = \frac{\frac{h_{1y} L}{\lambda}\mu_n + \frac{h_{2y} L}{\lambda}\mu_n}{\mu_n^2 - \frac{h_{1y} h_{2y} L}{\lambda^2}};(32)$$

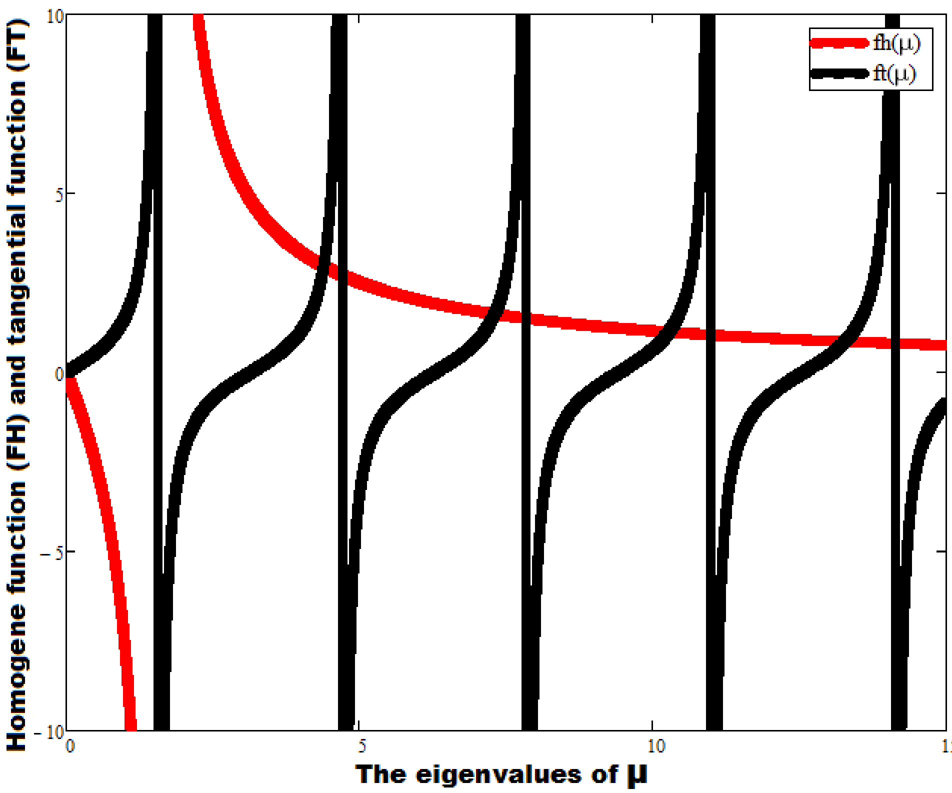

Figure 3:- Curve of the following transcendent equation.

The intersection of the two curves fh (μ_n) and ft (μ_n) corresponds to the solution.
Table 1 summarizes the eigenvalues found of μ_n

Table 2:- The eigenvaluesμ_n the equation.

n	1	2	3	4	5
μ_n	4,5	7,5	10,4	13,4	16,5

$$\theta(u;v,\tau)=\frac{T(x,y,h_{1x},h_{2x},h_{1y},h_{2y},t)-T_a}{T_i-T_a};(33)$$

$$T(x,y,h_{1x},h_{2x},h_{1y},h_{2y},t)=T=T_a+(T_i-T_a)\theta(u;v,\tau);(34)$$

The general solution of temperature:

$$T=T_a+(T_i-T_a)\sum_n\left[a_n\left(\cos\left(\beta_n\frac{x}{L}\right)+\frac{\frac{h_{1x}L}{\lambda}}{\beta_n}\sin\left(\beta_n\frac{x}{L}\right)\right)c_n\left(\cos\left(\mu_n\frac{y}{L}\right)+\frac{\frac{h_{1y}L}{\lambda}}{\mu_n}\sin\left(\mu_n\frac{y}{L}\right)\right)\right]e^{-\frac{\alpha t}{L^2}\gamma^2};(35)$$

Heat flux density:

We get the expression for the density of the heat flow (or surface heat flow)
Which is the heat flux per unit area (W.m^{-2}) as follows:

$$\vec{\varphi}(x,y,h_{1x},h_{2x},h_{1y},h_{2y},t)=-\lambda\overrightarrow{grad}T(x,y,h_{1x},h_{2x},h_{1y},h_{2y},t);(36)$$

$$\vec{\varphi}(x,y,h_{1x},h_{2x},h_{1y},h_{2y},t)=\overrightarrow{\varphi_x}(x,y,h_{1x},h_{2x},h_{1y},h_{2y},t)+\overrightarrow{\varphi_y}(x,y,h_{1x},h_{2x},h_{1y},h_{2y},t);(37)$$

From these two expressions we get, the final expression of the heat flux density

$$\varphi(x,y,t)=\lambda(Ti-Ta)\left[\left[\sum_{n}an\left(-\frac{\beta n}{L}\sin\left(\beta n\frac{x}{L}\right)+\frac{Bi1x}{L}\cos\left(\beta n\frac{x}{L}\right)\right)cn\left(\cos\left(\mu n\frac{y}{L}\right)+\frac{Bi1y}{L}\sin\left(\mu n\frac{y}{L}\right)\right)\right]^{2}+\left[\sum_{n}cn\left(-\frac{\mu n}{L}\sin\left(\mu n\frac{y}{L}\right)+\frac{Bi1y}{L}\cos\left(\mu n\frac{x}{L}\right)\right)an\left(\cos\left(\beta n\frac{x}{L}\right)+\frac{Bi1x}{L}\sin\left(\beta n\frac{x}{L}\right)\right)\right]^{2}\right]^{\frac{1}{2}}e^{-\frac{\alpha t}{L^{2}}\gamma^{2}};(38)$$

Results And Discussion:-

Evolution of the temperature and the density of the heat flow as a function of the depth for different values of the exchange coefficient

Figures 4 and 5 show the evolution of temperature and heat flux density as a function of depth under the influence of the thermal coefficient at the front face in the typha panel.

We note a weak variation of the temperature and the density of heat flow according to the depth for the weak values of the depth. In this zone the temperature and the heat flux density are maximum. The temperature is close to that of the ambient environment, i.e. 30^0 C. This zone corresponding to a long period of excitement, the typha does not have time to relax. Thus, it behaves as a thermal conductor.

Beyond this depth, the temperature decreases and tends towards that of the material in the initial state. This favors the heating of the latter, translating the storage of a large quantity of heat. This is more accentuated at the surface but decreases at depth. Consequently, the most favorable depths for heat storage are values greater than 0.01m. The influence of depth is highlighted.

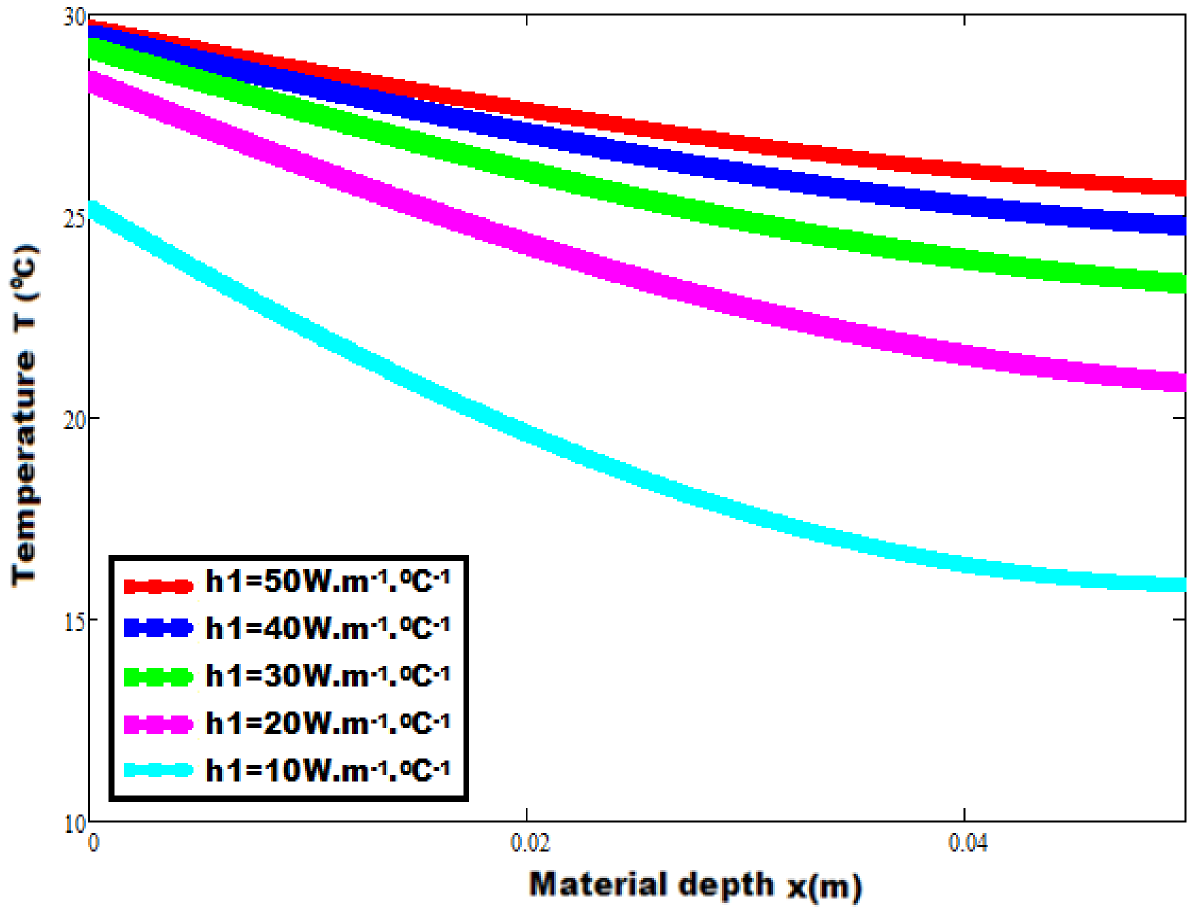

Figure 4:- Temperature as a function of material depth. h_2=0.005W.m^{-2}.C^{-1}; t=10s.

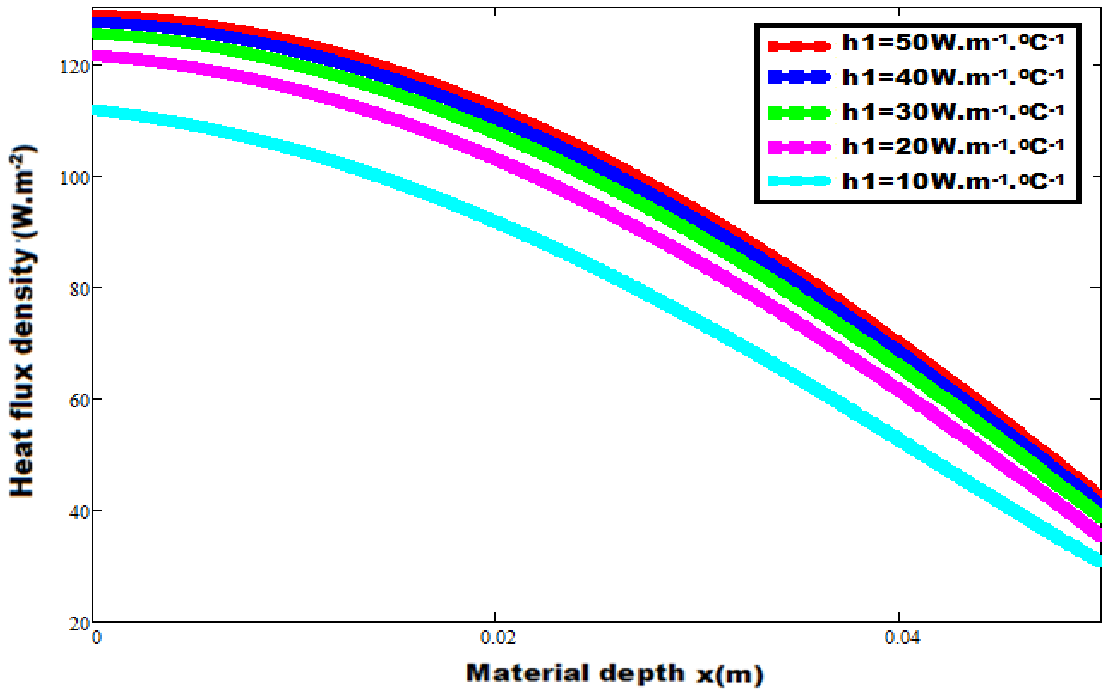

Figure 5:- Heat flux density as a function of material depth. h_2=0.005W.m^{-2}.C^{-1} ; t=10s.

3.2 Evolution of the Temperature and the Density of the heat flow as a function of time

Figures 6 and 7 give the temperature and heat flux density as a function of time under the influence of the heat exchange coefficient at the front face.

These figures show that the wall heats up as a function of time, reflecting the storage of thermal energy. The temperature exchange for the different values is all the more important as the thermal coefficient is high.

The heat flux density decreases inside the material as a function of time under the influence of the coefficient at the front face. This decrease is due to a loss of heat in the typha-clay material.

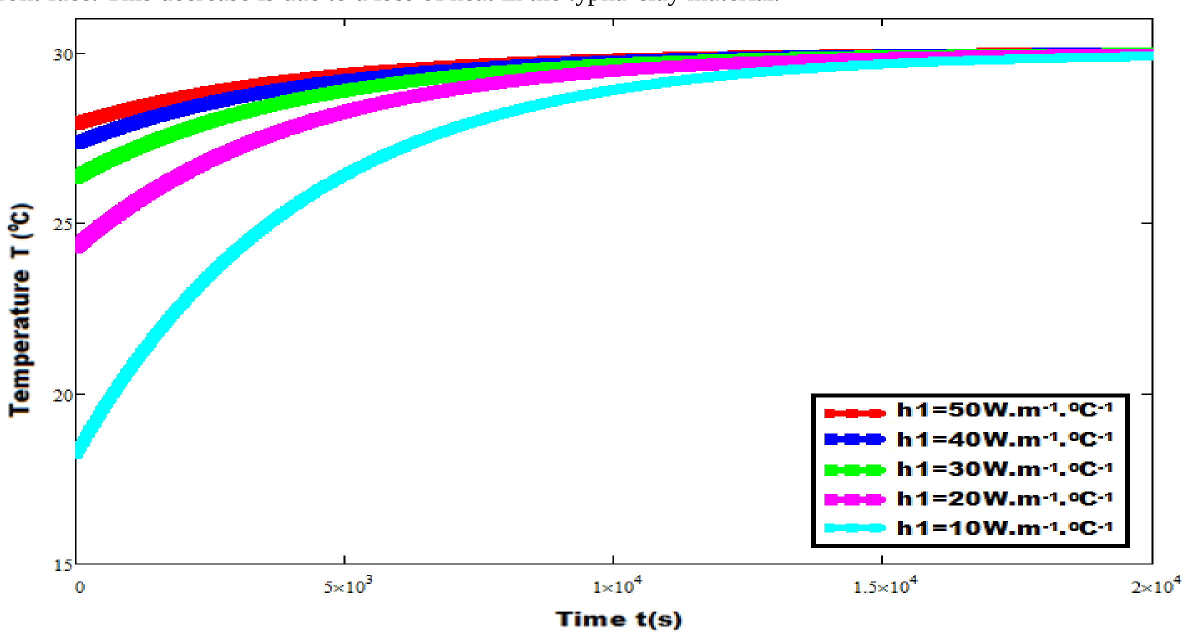

Figure 6 : Evolution of the temperature as a function of material time. x=0.01m ; h_2=0.005W.m^{-2}.C^{-1}

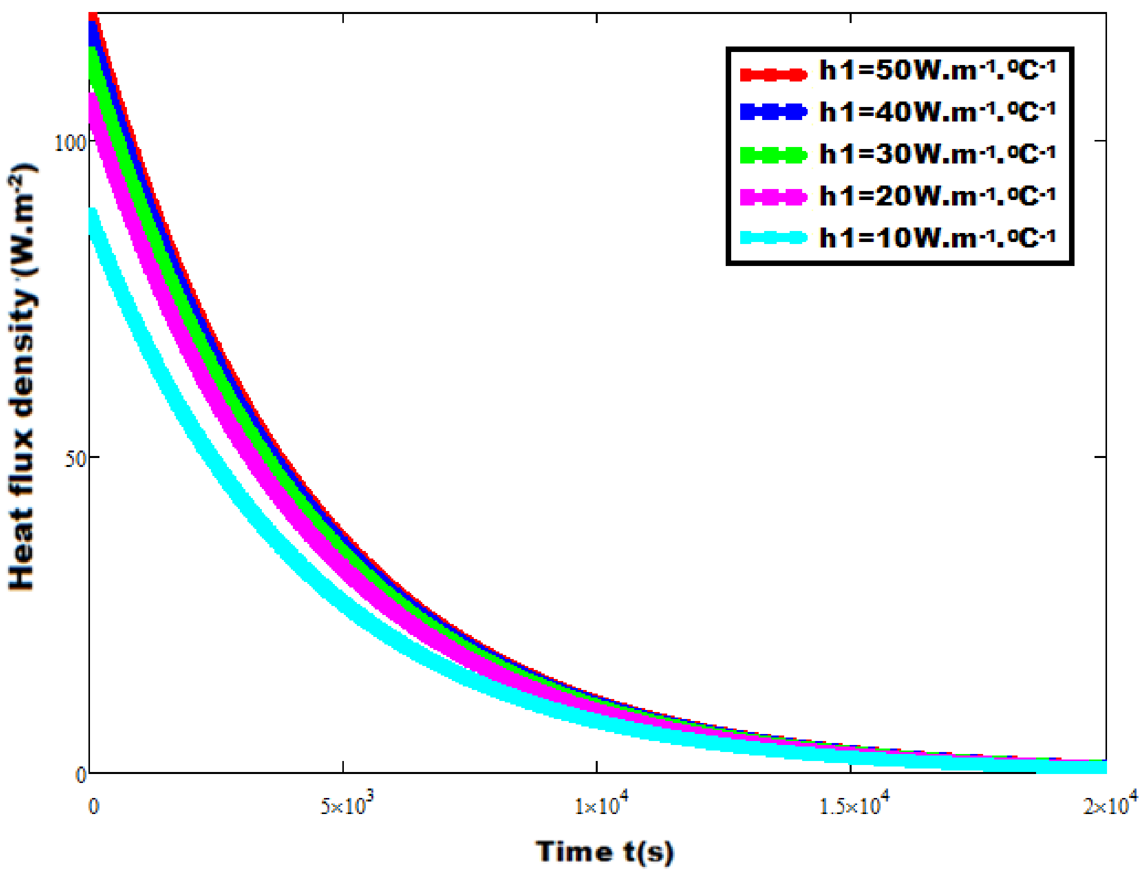

Figure 7:- Evolution of the heat flux density as a function of time. x=0.01m ; h_2=0.005W.m^{-2}.C^{-1}

Conclusion:-

The quality of the material in thermal insulation is highlighted by studying the thermal behavior of the typha-clay material through a modeling of the temperature of the heat flux density.

The influence of the external parameter such as the heat exchange coefficient is given from the temperature and heat flux density profiles in the typha-clay panel. The modeling of the temperature and the heat flux density made it possible to highlight the quality of the typha-clay material in thermal insulation.

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