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Research Article

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Transitory regime heat transfer study in a short hollow cylinder rolls up with a thermal insulating material Linen: thermal exchange coefficient influence

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Abstract In this work, we study in transitory regime, the thermal behavior of a system constituted by a short hollow cylinder rolls up with by some linen as heat insulator. The cylinder contains a fluid in which the temperature is higher than the outside.
From the heat equation, the temperature's expression is obtained by the variables separation method. As regards the heat flow density, it is deducted from the FOURIER law.
The temperature and heat flow density profiles according to the time, the linen thickness and the cylinder height has permitted to appreciate the fluid cooling phenomenon. The influence of the thermal exchange coefficient on the heat flow is highlighted at the internal wall proximity.

Keywords hollow cylinder-linen- thermal behavior-thermal exchange coefficient- transitory regime

1. Introduction

The use of the local materials in housing environment under the constraints of thermal comfort and energy saving crosses by the studies of their thermal and energy behavior by means of computing simulation [1] tools. The Laplace equation solutions or the heat equation proposed are numerous and often complex according to established model of study. Some authors proposed resolution methods of the equation in static regime [2, 3], in dynamic transitory regime [4] or in dynamic frequency modulation [5].
Besides, the thermal transfer studies of a cylinder made with local materials were proposed.Other authors have proposed the thermal transfer of a cylinder made from local materials [6,7] or the effect of the convective heat flux [8,9]. But the authors considered a full model cylinder which raise an exploitation problem and an important quantity of insulating material to be used.
In this work, we propose an analytical resolution method for the heat equation in a short hollow cylinder model. The temperature and the heat density flow curve profiles according to the linen thickness, the cylinder height and the time are presented. The thermal exchange influence coefficient characterizing the heat exchange between a fluid and a side of a solid is proposed.

2. Theoretical

2.1. Studied device

We consider a hollow cylinder rolled up by a material with e as the thickness, λ the thermal conductivity, R_1 as the internal radius and R_2 the outside radius, H represents the height. The used material is supposed to be homogeneous with a thermal conductivity $\lambda=0.037 W.m^{-1}.K^{-1}$and $\alpha=8.10^{-7}$ $m^2.s^{-1}$asthe thermal diffusivity. The temperatures and exchanges coefficients of the internal and external faces being respectively T_0, h_1 and T_a, h_2. We suppose that the flow is going to be made according to the longitudinal axis and the radial axis. However, we will particularly put interest into the heat losses at the level of the cylinder exterior side. The figure1 represents the experimental device.

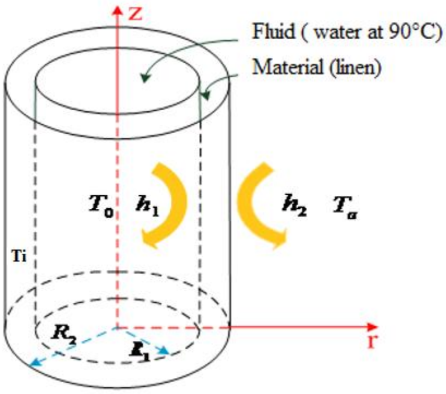


Figure 1: Experimental device, linen hollow cylinder

h_1 and h_2 are the thermal exchanges coefficients at the inner and exterior side of the cylinder;

T_0 and T_a are the ambient temperatures following the radial direction ringside and outside of the cylinder with

$T_0 = 90°C$ and $T_a = 35°C$, $T_i = 25°C$ Initial material's temperature.

2.2. Heat equation analytical solution

The heat equation, without source nor heat sink, is given by the following expression:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 \quad (1)$$

T=T(r, z, t) material's temperature

Ti: material's initial temperature

$$\alpha = \frac{\lambda}{\rho.c}$$ (2): thermal diffusivity coefficient ($m^2.s^{-1}$)

λ is the thermal conductivity ($W.m^{-1}K^{-1}$) and ρ ($kg.m^3$) is the material density

Boundary conditions:

$$\left.\frac{\lambda \partial T}{\partial r}\right|_{r=R_1} = h_1\left[T(R_1, z, t) - T_0\right] \quad (3)$$

$$-\left.\frac{\lambda \partial T}{\partial r}\right|_{r=R_2} = h_2\left[T(R_2, z, t) - T_a\right] \quad (4)$$

$$\left.\frac{\lambda \partial T}{\partial z}\right|_{z=0} = h_3\left[T(r, 0, t) - T_O\right] \quad (5)$$

$$-\left.\frac{\lambda \partial T}{\partial z}\right|_{z=H} = h_4\left[T(r, H, t) - T_O\right] \quad (6)$$

$$T(r, z, 0) = T_i \quad (7)$$

We proceed to the variable chance as following:

$$\varphi(r,z,t) = T(r,z,t) - T_i \quad (8)$$

Equation (1) can be written into:

$$\frac{\partial^2\varphi}{\partial r^2} + \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\varphi}{\partial\theta^2} + \frac{\partial^2\varphi}{\partial z^2} - \frac{1}{\alpha}\frac{\partial\varphi}{\partial t} = 0 \quad (9)$$

And boundary conditions become:

$$\left.\frac{\lambda\partial\varphi}{\partial r}\right|_{r=R_1} = h_1[\varphi(R_1,z,t) - \phi 0] \quad (10) \qquad \text{with } \phi 0 = T_i - T_0$$

$$-\left.\frac{\lambda\partial\varphi}{\partial r}\right|_{r=R_2} = h_2[\varphi(R_2,z,t) - \phi a] \quad (11) \qquad \text{with } \phi a = T_i - T_a$$

$$\left.\frac{\lambda\partial\varphi}{\partial z}\right|_{z=0} = h_3\varphi(r,0,t) \quad (12)$$

$$-\left.\frac{\lambda\partial\varphi}{\partial z}\right|_{z=H} = h_4\varphi(r,H,t) \quad (13)$$

We make temperature decomposition in product of functions into this form:

$$\varphi(r,z,t) = R(r).Z(z).Y(t).\cos(\theta) \quad (14)$$

The heat equation leads to the following equations:

$$\frac{1}{R(r)}\left[\frac{\partial R(r)}{\partial r^2} + \frac{1}{r}\frac{\partial R(r)}{\partial r}\right] - \frac{1}{r^2} + \frac{1}{Z(z)}\frac{\partial^2 Z(z)}{\partial z^2} = \frac{1}{Y(t)}\frac{1}{\alpha}\frac{\partial Y(t)}{\partial t} = -w^2 \quad (15)$$

$$\begin{cases} \dfrac{\partial Y(t)}{\partial t} + \alpha\omega^2 Y(t) = 0 \\ \dfrac{\partial^2 Z(z)}{\partial z^2} + \omega^2 Z(z) = 0 \\ \dfrac{1}{R(r)}\dfrac{\partial^2 R(r)}{\partial r^2} + \dfrac{1}{r}\dfrac{1}{R(r)}\dfrac{\partial R(r)}{\partial r} - \dfrac{1}{r^2} = 0 \end{cases} \Rightarrow (16) \qquad \begin{cases} Y(t) = Ke^{-\alpha\omega^2 t} \\ Z(z) = A_1\cos(\omega z) + A_2\sin(\omega z) \\ R(r) = \dfrac{1}{2}C_1 r + \dfrac{C_2}{r} \end{cases} (17)$$

The following boundary conditions in z axis allow us to have the transcendent equation

$$A_2 = \frac{h_3}{\lambda\omega}A_1 \quad (18) \qquad \tan(\omega.H) = \frac{\lambda\omega(h_4 + h_3)}{\lambda^2\omega^2 - h_4 h_3} \quad (19)$$

Figure 2 gives different values of ω

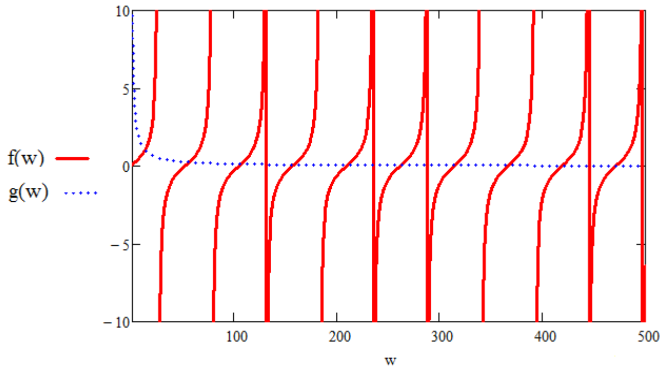


Figure 2: Graphical determination of transcendent equation roots

Table 1: Different values of ω

n	1	2	3	4	5	6	7	8	9

ω_n	19.5	62	111	161.5	214.5	264.5	316.5	419	473

The general equation:

$$\varphi(r,z,t)=\sum_{n=1}^{\infty}\left(\frac{1}{2}C_{n1}r+\frac{C_{n2}}{r}\right)\left(\cos(\omega_n z)+\frac{h3}{\lambda\omega_n}\sin(\omega_n z)\right).\cos\theta e^{-\alpha\omega_n^2 t} \qquad (20)$$

The boundary conditions following r allows us to determine C_{n1} and C_{n2}

$$K_n=\left(\frac{\sin(\omega_n H)+2\omega_n H}{8}+\frac{h3-h3\cos(2\omega_n H)}{8\lambda\omega_n}\right)\left(1+e^{-\alpha.\omega_n^2\tau}\right) \qquad (21)$$

$$P_{n1}=\sin(\omega_n H).h_1.\phi 0 \qquad (22)$$

$$P_{n2}=\sin(\omega_n H).h_2.\phi a \qquad (23)$$

$$C_{n1}=\frac{P_{n1}\left(\frac{h_2.R_2-\lambda}{K_n R_2^{\,2}}\right)-P_{n2}\cdot\left(\frac{\lambda+h_1R_1}{R_1^{\,2}.K_n}\right)}{\left(\frac{\lambda-h_1.R_1}{2}\right)\left(\frac{h_2R_2-\lambda}{R_2^{\,2}}\right)+\left(\frac{\lambda+h_2.R_2}{2}\right)\left(\frac{\lambda+h_1R_1}{R_1^{\,2}}\right)} \qquad (24)$$

$$C_{n2}=\frac{P_{n2}\cdot\left(\frac{\lambda-R_1.h_1}{2.K_n}\right)+P_{n1}\left(\frac{\lambda+R_2h_2}{2.k_n}\right)}{\left(\frac{\lambda-h_1R_1}{2}\right)\left(\frac{h_2R_2-\lambda}{R_2^{\,2}}\right)+\left(\frac{\lambda+h_2R_2}{2}\right)\left(\frac{\lambda+h_1R_1}{R_1^{\,2}}\right)} \qquad (25)$$

Temperature final equation:

$$T(r,z,h_1,h_2,t)=Ti+\sum_{n=1}^{\infty}\left(\frac{1}{2}C_{n1}r+\frac{C_{n2}}{r}\right)\left(\cos(\omega_n z)+\frac{h_3}{\lambda w_n}\sin({}_n z)\right).e^{-\alpha.w_n^2 t} \qquad (26)$$

The thermal flow density is given by:

$$\vec{\phi}(r,z,h_1,h_2,t)=-\lambda\,\overrightarrow{grad}\,T(r,z,h_1,h_2) \qquad (27)$$

$$\vec{\phi}=\vec{\phi}r+\vec{\phi}z \qquad (28)$$

$\vec{\phi}r$: The thermal flow density following r direction

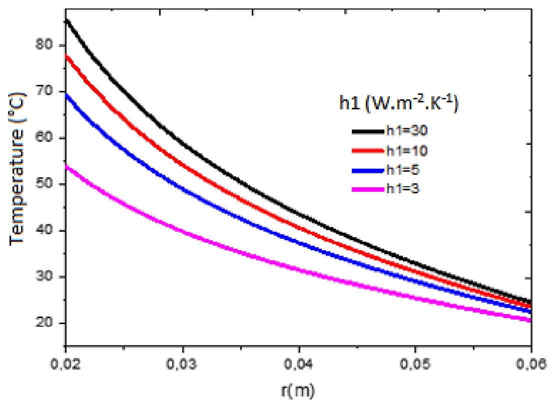
$\vec{\phi}z$: The thermal flow density following z direction

The global thermal flow density is obtained by calculating the module:

$$\phi(r,z,h_1,h_{21},t)=\sqrt{\phi r(r,z,h_1,h_2,t)^2+\phi z(r,z,h_1,h_2)^2} \qquad (29)$$

3. Results and Discussed

The following figures present the temperature and the flow density according to the insulating material thickness, the time and the cylinder height under the influence of the thermal exchange coefficient h_1.



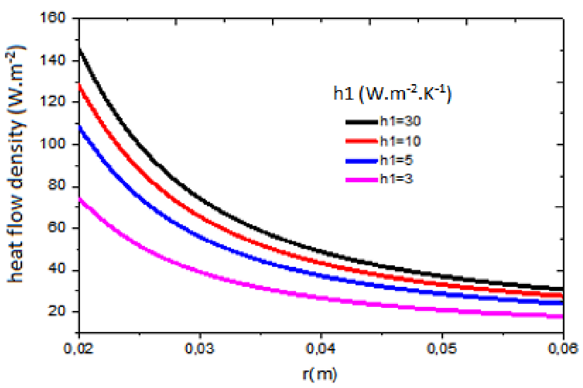
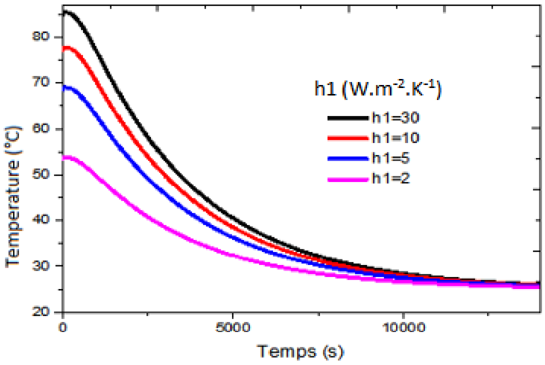


Figure 3: Temperature evolution according to the radius depth r. t=100s; z=0.03m; h_2=5W.m^{-2}.C^{-1}

Figure 4: Heat flow density evolution according to the cylinder radius r. t=100s; z=0.03m; h_2=5W.m^{-2}. °C



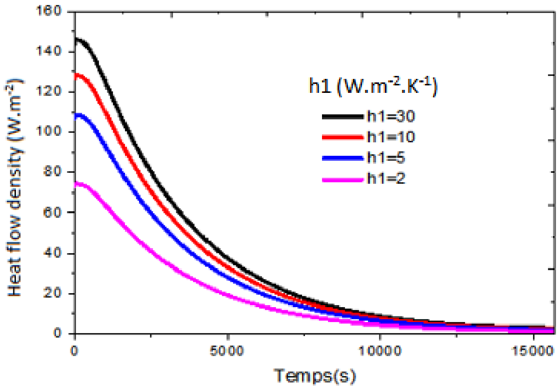
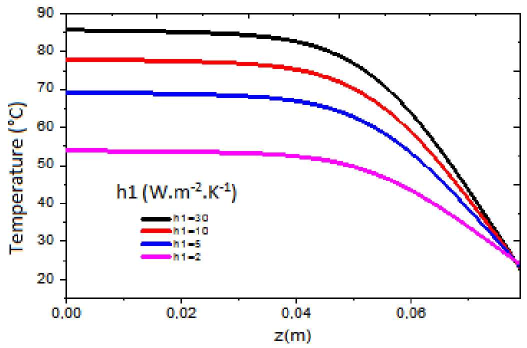


Figure 5: Temperature evolution according to the time. r=0.02m ; z=0.03m ; h_2=5W.m$^{-2. K-1}$

Figure 6: Heat flow density evolution according bto the time. r=0.02m ; z=0.03m ; h_2=5W.m$^{-2. K-1}$



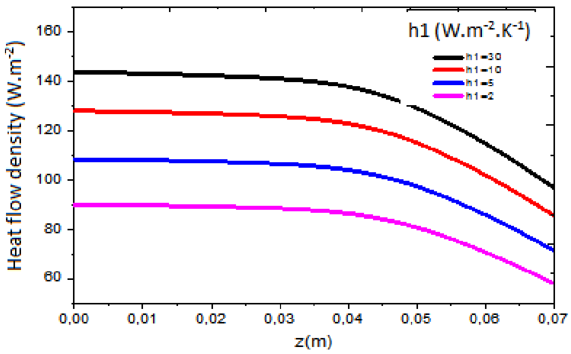
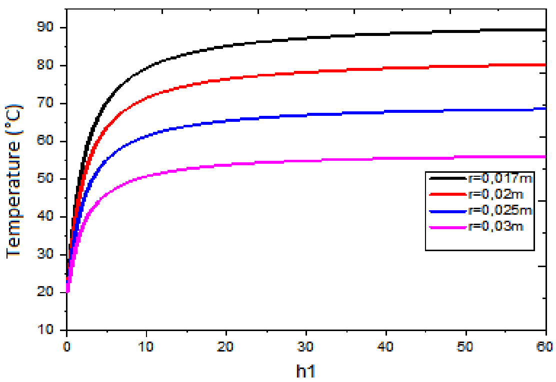


Figure 7: Temperature evolution according to the cylinder high t z(m).h_2=5W.m^{-2}.K^{-1}; r=0.02 ; t=100s

Figure 8 :Heat flow density profile according to z(m).h_2=5W.m^{-2}.K^{-1}, r=0.02m ; t=100s



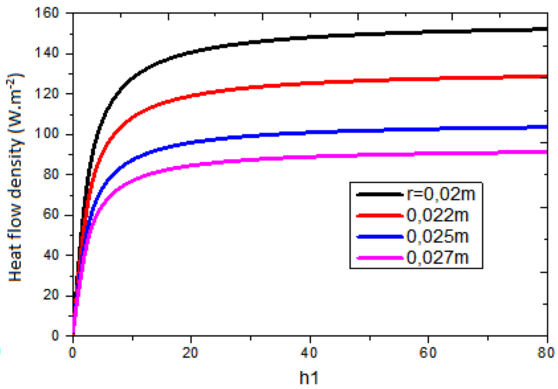


Figure 9: Temperature evolution according to the exchange coefficient h_1. t=100s ; h_2=5W.m^{-2}.K^{-1} ; z=0.03m

Figure 10: Heat flow density according to the exchange coefficient h_1. t=100s;h_2=5W.m^{-2}. K^{-1} ; z=0.03m

The temperature curves and the thermal flow density give the thermal behavior in the material.

Figures 3 and 4 present the same profile. In the front face r=0.02m, the material absorbs some heat and warms up. Inside the material, the temperature and the density decreases and tend to the initial temperature of this one. The decrease of the flow density translates a transmitted heat loss, which is, besides stored in the neighborhood of the front face of the material. This heat quantity transmitted is more important when the thermal exchange coefficient in the front face is high. For low values of the thermal exchange coefficient, we notice an important heat loss in the interface of the material r=0.02m meaning relaxation phenomenon.

For figures 7 and 8, the temperature and the maximal density in z=0 present a low variation for z = 0.04m then decreases regularly by approaching the side face. When z increase, the quantity of heat transmitted is less important. However, because of the dimensions of the material, a part of the energy reaches at the level of side face and is passed to ambient. Heat absorbed by the material is important when the exchange thermal coefficient is raised, which allows to avoid the phenomena of relaxations.

Figures 5 and 6 show respectively the temperature and the thermal flow density evolution in time in the neighborhood of the front face under the influence of the thermal exchange coefficient h1. We notice a temperature and flow density decrease according to the time. The thermal exchange coefficient decrease lead to a fluid cooling. Indeed, the low values of the thermal exchange coefficient correspond to low thermal exchanges. For a time between 0 and 5000 seconds, the temperature and the density decrease slightly to achieve 41°C. The insulating material also presents a good thermal inertia [10-12]. The fluid inside the cylinder cools.

In figures 9 and 10, we observe practically the same profile. In a point in the material, the temperature and the thermal flow density rise exponentially according to h1, then reached a landing which corresponds to the maximal energy stored in this point. These curves show that the temperature decreases in the material. Indeed, the presence of the landing shows that the temperature does not increase almost any more, the material seems stored the heat energy. Thus there is a situation of thermal saturation when the cylinder radius is less important. This shows that the material possesses a capacity of storage or waste of energy.

4. Conclusion

The heat transfer study of a short hollow cylinder in transitory regime was proposed for the linen material characterization. From the mathematical model, the curves of temperature and heat flow evolution allowed to show the thermal behavior of the material and the optimal ranges of the thermal exchange coefficient leading to an important heat transfer. The influence of the thermal exchange coefficient shows the necessity of mastering the internal and outside environment of the material.

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