The 2017 World Congress on
Advances in Nano, Bio, Robotics and Energy (ANBRE17)
28 August - 1 September, 2017, Ilsan(Seoul), Korea

Parametric investigation of thermal walls for low income families' homes

*Juliana Avila[1] and Kamal Abdel Radi Ismail[2]

[1)2)]*State University of Campinas, Faculty of Mechanical Engineering, Energy Department, Mendeleiev street, 200, Cidade Universitária "Zeferino Vaz", Postal Code: 13083-860, Barão Geraldo, Campinas (SP), Brazil.*
[1)] *j.avila@wika.com.br*

ABSTRACT

Active thermal comfort in residential buildings contributes 30 to 40% of the energy consumption and this directly impacts the greenhouse gas emissions and the global energy demand. Low income populations' homes are usually made of relatively cheap material and thermal comfort is usually a major problem. In an attempt to attenuate this problem, this paper proposes cheap thermal walls as construction elements for low energy houses where the mortar and bricks materials contain biomass fibers. The problem is formulated based on one dimensional model and solved numerically by finite difference technique. Numerical tests were realized to optimize the numerical grid. Simple wall with some variants such as biomass addition, paints, thickness and absorptivity were investigated. Results indicated that increasing wall thickness reduces the internal peak temperature and delays its occurrence. Bright paints and wall planted vegetation have similar effects as increasing wall thickness. Low thermal conductivity material and use of surface finishing mortar and bricks mixed with dry biomass helps reducing the solar heat gain, internal ambient temperature and increasing the time lag.

Keywords: Thermal walls; Passive thermal comfort; Low energy dwellings; Modeling of thermal walls.

[1)] Graduate Student
[2)] Professor

Nomenclature and abbreviations

a = Width of the external wall (1st wall);
b = Width of spacing between walls (stagnant air gap);
c = Width of the internal wall (2nd wall);
i = regions a, b, c;
x = Total width of the wall;
h_{EXT} = Heat transfer coefficient of the external ambient (W/m². ºC);
h_{INT} = Heat transfer coefficient the internal ambient (W/m². ºC);
ID = Intensity of direct radiation (MJ/m^2);
Id = Intensity of diffuse radiation (MJ/m^2);
k_a = Thermal conductivity of the external wall (W/m.ºC);
α_s = Thermal diffusivity of the external wall (m²/s);
ε = Emissivity;
α = absorptivity;
$Q_s(t)$ = Intensity of incident solar radiation on a surface (MJ/m²);
Bi = Biot number;
*RT** = Ratio of maximum internal temperature/Maximum external temperature;
RT = Ratio of internal temperature/ External temperature;
T_a = Temperature of the external side of the wall (ºC);
T_{AR} = Temperature of atmospheric air (^{o}C);
T_{EXT} = Temperature of the external ambient (^{o}C);
T_{INT} = Temperature of the internal ambient (^{o}C);
T_i = Temperature of region I (^{o}C);
T_S = Solar temperature, (ºC);

1. INTRODUCTION

The contribution of heating and cooling for thermal comfort in residential and commercial buildings is usually around 30 to 40% of the energy bill. This consumption directly impacts the greenhouse gas (GHG) emissions and increases global energy demand and consumption, creating problems of energy distribution and severe energy demand peaks during certain hours of the day. Hence, intensive efforts are being encouraged to design low energy buildings and utilize construction elements with specific thermal characteristics, which helps establishing passive thermal comfort. Construction elements that have high thermal capacity and big effective thermal mass are possible candidates for low energy residences and buildings. Increasing the heat capacity of walls, ceiling and floor of buildings may be enhanced by encapsulating or embedding suitable PCMs within these surfaces. Increasing the thermal storage capacity of a building can increase human comfort by decreasing the frequency of internal air temperature swings so that the indoor air temperature is closer to the desired temperature for a longer period (Isa et al. 2010) and (Kuznik et al. 2011).

Bernard et al. (1985) reported the results of a comparative experimental study on latent and sensible heat thermal walls. The energy gain of the walls and the temperature variations of the inside room were compared with a concrete wall. The advantage of the latent heat wall over the concrete wall is the mass which was 1/12 the mass of the concrete wall, thus suitable for retrofit.

The use of phase change material (PCM) has been recognized as advanced energy technology in enhancing energy efficiency and sustainability of buildings since it provides a potential for a better indoor thermal comfort and reduces global energy consumption (Ismail and Castro 1997).

Solar walls have been studied for decades as a way of heating building from a renewable energy source. This effect is due to their storage capacity. However, this increases their weight and volume, which limits their integration into existing building. To alleviate this problem, storage mass is replaced by a suitable phase change material that melts completely before the sunset and re-solidifies completely before the sunrise. This leads to a significant reduction of the building energy consumption. The same technology of incorporating PCM in walls can be used for roofs and floors to enhance thermal comfort in the interior space of a building and economize energy (Kuznik et al. 2011).

Tyagi and Buddhi (2007) presented a comprehensive review of various possible methods for heating and cooling in buildings such as PCM Trombe wall, PCM wallboards, PCM shutters, building blocks with PCM , air-based heating systems, floor heating, ceiling boards, etc. All systems have good potential for reducing the energy demand of heating and cooling in buildings.

It has been demonstrated that increasing the thermal storage capacity of a building can enhance human comfort by decreasing the frequency of internal air temperature swings, as in Isa et al. (2010), Kuznik et al. (2011) and Zhu et al. (2009).

In conventional buildings thermal mass is a permanent building characteristic depending on the building design. However, none of the permanent thermal mass concepts are optimal in all operational conditions. Hoes et al. (2011) proposed a concept that combines the benefits of buildings with small and big thermal mass by applying hybrid adaptable thermal storage systems and materials to a lightweight building. Calculations showed heating energy demand reductions of up to 35% and increased thermal comfort compared to conventional thermal mass concepts.

As mentioned before, thermal mass combined with other passive strategies can play an important role in buildings energy efficiency, minimizing the need of space-conditioning mechanical systems. However, the use of lightweight materials with low thermal mass but with low thermal conductivity is becoming increasingly common and frequently is extended to the treatment of roofs and floors, as in Rostamizadeha et al. (2012), Soares et al. (2013), Chou et al. (2013), Guichard et al. (2014) and Tokuç et al. (2015).

The objective of the present study is to investigate the behavior of thermal walls as elements in low energy consumption buildings. The problem is formulated based on one dimensional model and solved numerically by finite difference technique. The simple wall configuration was investigated including external surface finish, low thermal conductivity material and biomass additives to surface finishing mortar. The influence of these variations on the internal ambient temperature and the time lag were calculated and discussed.

2. FORMULATION OF THE PROBLEM

The thermal wall is composed of plane surface subject to incident solar radiation, thermal convection on the external surface and the internal ambient surface and conduction across the solid wall. The assumptions adopted here include no humidity migration (dry wall), initial uniform wall temperature and constant thermo physical properties of construction material. The wall configuration treated in this study is shown in Fig. 1.

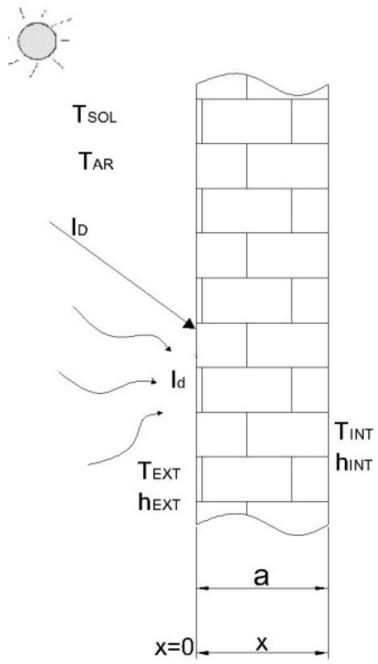

Fig. 1 Geometry details of the investigated simple wall

The total instantaneous radiation incident over the external surface of the wall is composed of direct radiation ID and diffuse radiation Id. From Kalogirou (2011) it is possible to estimate the intensity of solar direct radiation during the required day period assuming a sunny day without clouds. To estimate the diffuse radiation the method due to Liu and Jordan (1960) was used.

Considering constant thermal conductivity, constant heat transfer coefficients, no internal heat generation the governing differential equation for heat conduction can be written in the form;

$$\frac{\partial^2 T}{\partial^2 x} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

The boundary condition on the external wall is taken as proposed by Srivastava (1980) and is written in the form;

$$-k_a \left.\frac{\partial T_a}{\partial x}\right|_{x=0} = h_{EXT}\left[T_s - T_a\right]_{x=0} \tag{2}$$

Where Ts is given by

$$T_S = \frac{\alpha_S Q_S(t) - \varepsilon \Delta R - h_{EXT} T_{AR}}{h_{EXT}} \tag{3}$$

Where

T_S = Solar temperature (ºC);

ΔR = Difference between incident solar radiation over the surface and radiation emitted by a Black body at the temperature of atmospheric air (kJ/m² h).

k_a = Thermal conductivity of the external wall (W/m.ºC);

α_s = Thermal diffusivity of the external wall (m²/s);

$Q_s(t)$ = Intensity of incident solar radiation on a surface (MJ/m²), calculated based on Kalogirou (2014) and Liu and Jordan (1960), and using available meorological data;

ε = Emissivity;

h_{EXT} = Global heat transfer coefficient between the external surface and external air (W/m². ºC);

T_a = Temperature of the external side of the wall (ºC);

T_{AR} = Temperature of the external atmospheric air (ºC), at a specific hour of the day calculated according to model proposed in ASHRAE (1993).

The boundary condition for the internal wall is written in the form valid for 0<x<a:

$$k_a \left.\frac{\partial T_a}{\partial x}\right|_{x=0} = k_a \left.\frac{\partial T_a}{\partial x}\right|_{x=a} \tag{4}$$

The boundary condition on the wall internal surface is:

$$k_a \frac{\partial T_a}{\partial x} = h_{INT}\left[T_a \; - T_{INT}\right] \tag{5}$$

Where

T_{INT} = Temperature of the internal ambient (ºC);

T_a = Temperature of the internal face of the wall (ºC);

The temperature of atmospheric air (T_{AR}) at a specific hour of the day calculated according to ASHRAE (1993) (ºC), is given by:

$$T_{AR}(t) = T_{\max} - \left(\frac{f}{100}\right)(T_{\max} - T_{\min}) \tag{6}$$

Where $T_{\max}$ e $T_{\min}$ are the monthly average maximum and minimum temperatures obtained from the region meteorological data, and (f) is a simulation factor for each hour of the day obtained from ASHARE (1993).

3. NUMERICAL TREATMENT

In order to solve the governing equations and the associated boundary conditions the finite difference method and the explicit formulation scheme were used to discretize the equations. A numerical program was developed and tested to optimize the computation grid. The time step $\Delta\tau$ was varied in the range 0.0005 to 0.005 s while the linear distance Δx across the wall was varied in the range of 0.015 to 0.16 m. The values used are $\Delta\tau$ = 0.0005 s and Δx =0.02 m.

3.1 Validation of the model

The present model and the numerical predictions were validated against numerical and experimental measurements realized by Castro (1991). First, the numerical predictions from the present study are validated against numerical results from Castro (1991) where he simulated two wall configurations of thickness of 120 and 240 mm, respectively. The brick is a brazilian standard brick of dimensions 240 mm x 120 mm x 60 mm, has a thermal conductivity of 0.7 W/m ºC, specific heat of 0.840 KJ/kg ºC, specific mass of 1600 kg/m³, absorptivity of 0.63 and emissivity of 0.93 where some of the values were determined experimentally while others were obtained from Çengel and Ghajar (2012). The convection heat transfer coefficients of the external side of the external wall and the internal side of the internal wall as 17.03 W/m²K and 8.0 W/m²K, respectively. In the simulation we considered the day number 344 of mean total radiation of 550 W/m², and maximum and minimum ambient temperatures 29 ºC e 17.9 ºC, respectively.

Fig. 2 shows a comparison between the present predictions and the results of Castro (1991) of the internal and external temperatures variation during the day for the case of simple wall. As can be observed, the agreement is good. Fig. 3 shows the hourly variation of the internal and external wall temperatures for the case of double wall indicating good agreement.

Experimental measurements realized by Marques (2007) on an experimental room of 3m x 3m x 3m of total wall thickness of 10 cm, situated in the city of São Luis, State of Maranhão, Brazil localized in a latitude of 2°35'and longitude of 44°12', respectively. For the day number 346 the total daily radiation was 381 W/m^2 having maximum and minimum ambient air temperatures of 34 ºC and 27 ºC, respectively. Further, the external and internal heat convection coefficients were considered as 17.03 W/m² and 8.0 W/m², respectively. The present predictions are compared with Marques (2007) experimental measurements in Fig. 4 indicating relatively good agreement. The differences between measurements and the numerical predictions at early hours of the day are due to the high humidity of the region of São Luis.

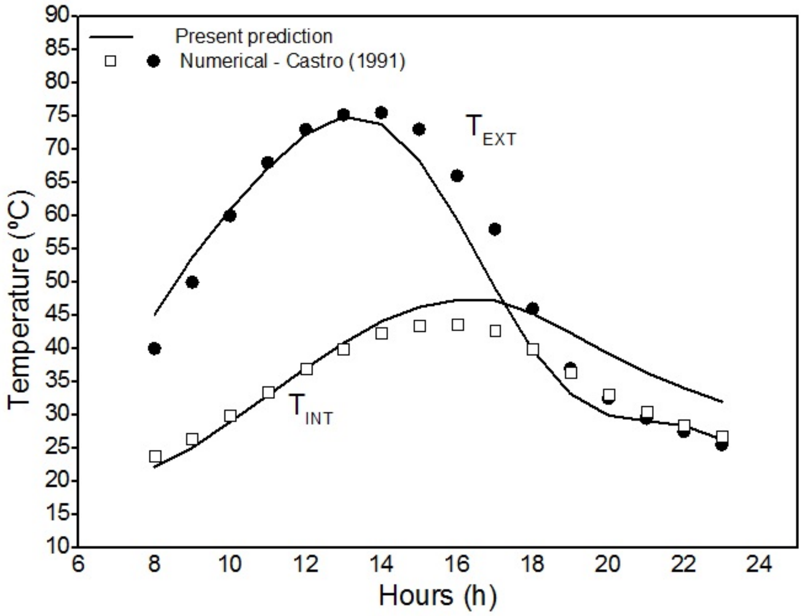

Fig. 2 Comparison of the predicted (T_{INT}) and (T_{EXT}) surface temperatures with the numerical results of the simple wall from (Castro 1991)

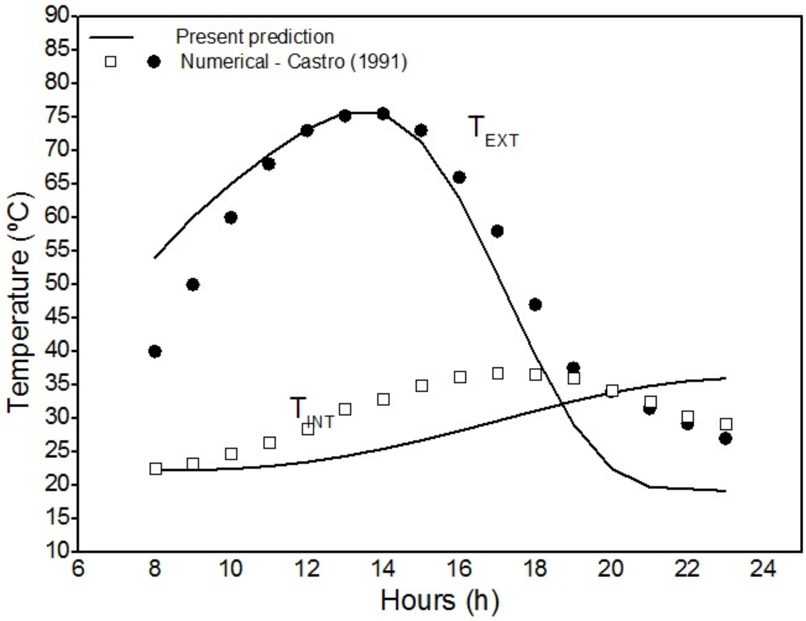

Fig. 3 Comparison of the predicted (T_{INT}) and (T_{EXT}) surface temperatures with the numerical results of the double wall from (Castro 1991)

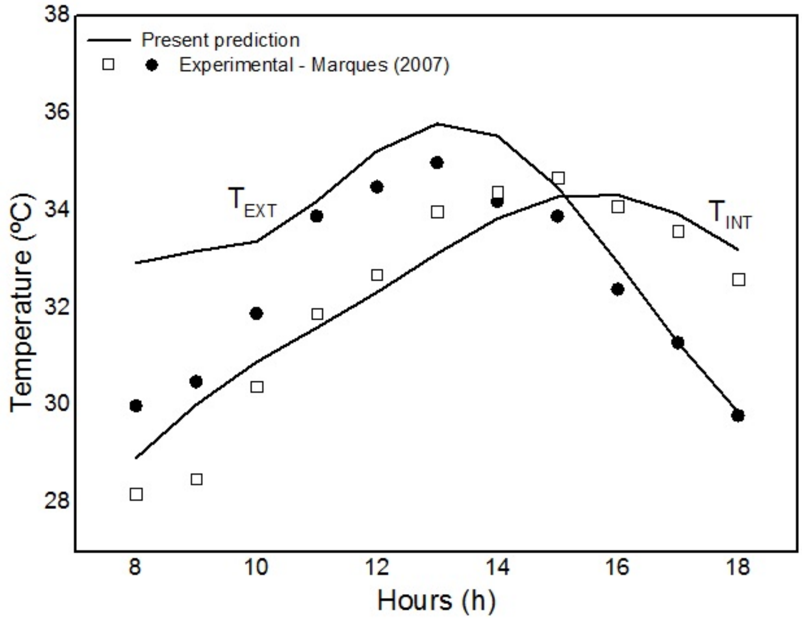

Fig. 4 Variation of the external and internal temperatures for the case of simple wall, (Marques 2007)

4. RESULTS AND DISCUSSION

A large number of numerical simulations were realized on the thermal wall to investigate the effects wall thickness, thermo- physical properties of construction materials, external finish of the wall and addition of biomass fibers. The meteorological and radiation data of the Campinas City, Brazil, shows a total daily average solar radiation of 38.1 MJ/m^2, visibility of 12 km, monthly average maximum, minimum temperatures of 26.8 ºC and 12.8 º C, respectively. The heat transfer coefficient on the internal side and external sides are 8.0 and 17.03 W/m². ºC, respectively.

4.1 Effect of varying wall thickness

The effect of varying the wall thickness on the external surface temperature is presented in Fig. 5 where the thermal diffusivity and the thermal conductivity were assumed as 0.52x10^{-6} m²/s, and 0.7 W/m.ºC, respectively and the wall thickness was varied from 6 cm to 48 cm.

As can be seen from Fig. 5 increasing the wall thickness increases the wall thermal resistance, reduces the heat transferred across the wall and consequently the maximum internal surface temperature. One can also observe the displacement of the maximum temperature and hence increasing the time lag for the maximum temperatures reaches the internal surface of the wall.

If we define RT* as the ratio of maximum internal temperature/Maximum external temperature, one can from Fig. 6 that as the wall thickness increases the thermal resistance increases, reduces the heat transfer rate and also the ratio of the maximum internal temperature to the maximum external temperature (RT*). The time lag defined as the time when the maximum temperature reaches the internal surface is found to increase with the increase of the wall thickness.

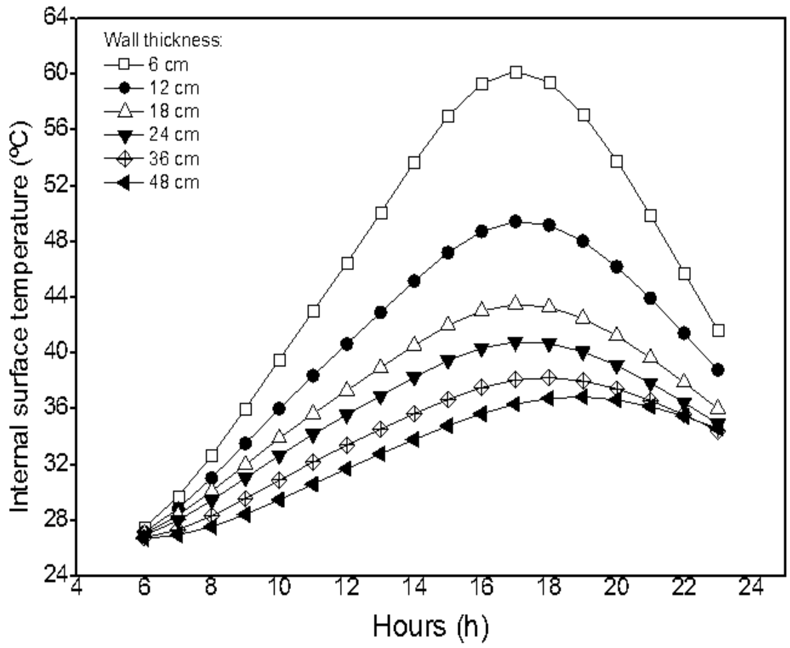

Fig. 5 Effect of varying the wall thickness on the internal surface temperature

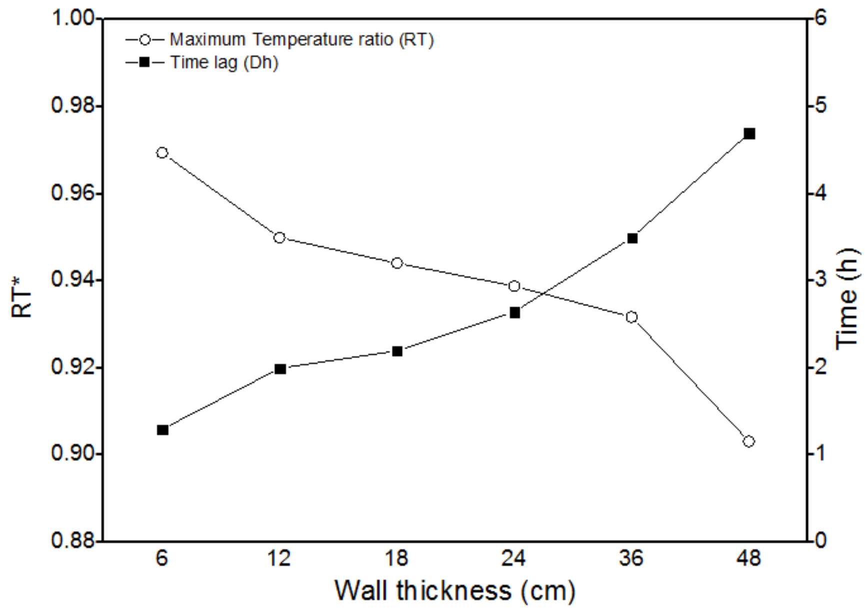

Fig. 6 Variation of the ratio of maximum internal temperature and time lag for different walls thickness

4.2 Effects of varying the thermal conductivity of the construction materials

Simulations were realized to investigate the effects of varying the thermal conductivity of the construction materials. The considered wall is of thickness 12 cm, specific mass of the bricks is 1600 kg/m3, specific heat of 0.92 kJ/kg ºC, absorptivity of 0.63 and emissivity 0.93, (Çengel and Ghajar 2012), while the thermal conductivity was varied from 0.1 to 0.9 W/m.ºC. As can be seen from Fig. 7 the low thermal conductivity increases the thermal resistance of the wall, reduces the heat transfer rate, attenuates the maximum internal temperature and increases the time delay.

Fig. 8 shows the variation of the ratio RT* with the variation of thermal conductivity of the construction material. As can be seen the increase of the thermal conductivity increases the ratio RT* and reduces the time lag. Typical construction materials have relatively high thermal conductivity in the range from 0.65 to 1.3 W/m.ºC.

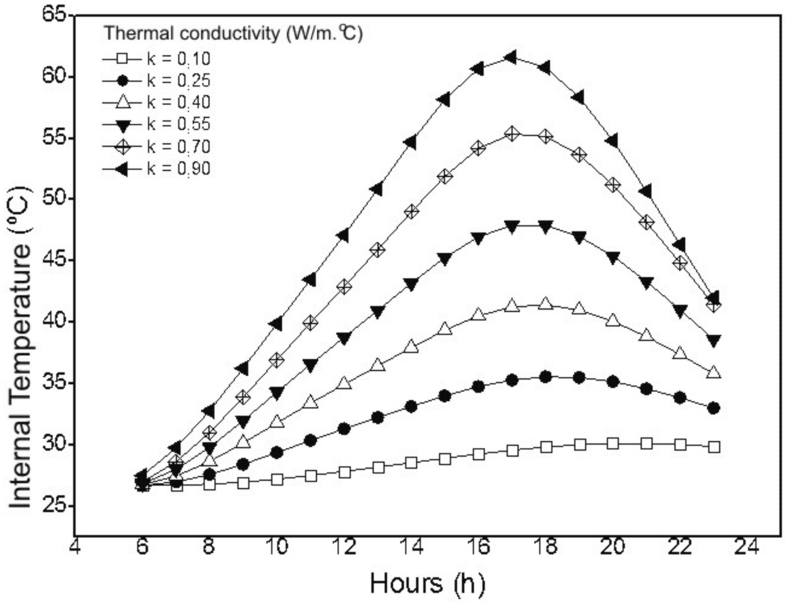

Fig. 7 Effect of varying the thermal conductivity on the internal surface temperature

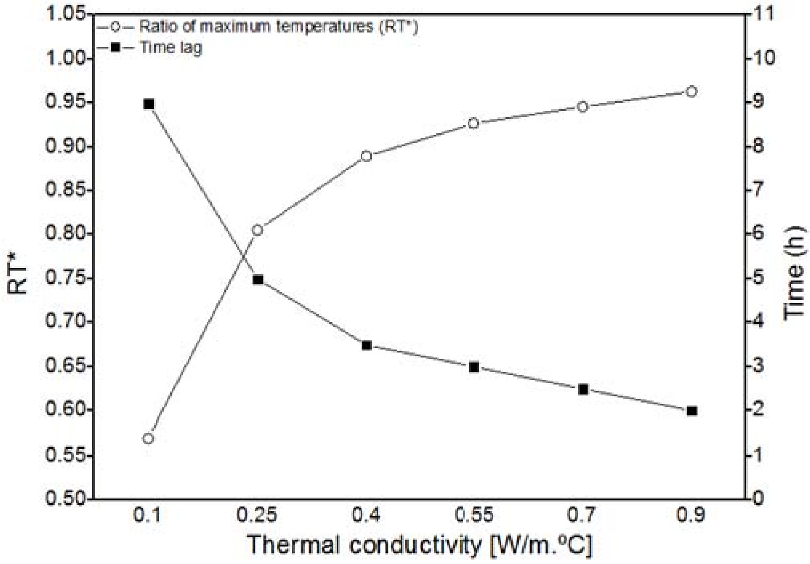

Fig. 8 Effect of the material thermal conductivity on the ratio RT* and time lag

4.3 Effects of the finishing material on external surface

The effects of the finishing material applied on the external wall surface, that is, its emissivity and absorptivity on the value of the maximum internal temperature and the corresponding time lag were investigated. The simulations were realized on wall of 12 cm thickness and thermal conductivity of the bricks of 0.9 W/m.ºC. The other properties are the same as in the preceding case. The emissivity and absorptivity values were obtained from Çengel and Ghajar (2012) and ASHRAE (1993) for white, black paints and planted vegetation on the external wall. Fig. 9 shows the hourly variation of the internal wall temperature due to variation of the external wall finish indicating that green covering can reduce the external temperature by about 50% while the white paint can absorb a small amount of incident radiation and consequently transmits less heat to the internal ambient.

Fig.10 shows the variation of the ratio of the internal to the external temperature and as can be observed the white painted wall seems to maintain nearly a constant temperature ratio which is helpful to maintain thermal comfort with marginal temperature swing.

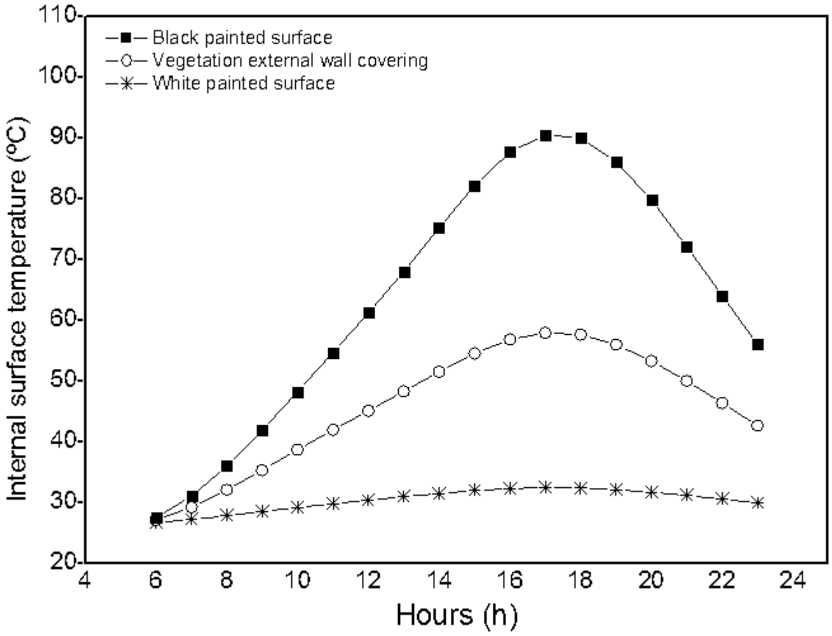

Fig. 9 Effect of the color of the external surface of the wall on the temperature of the internal surface

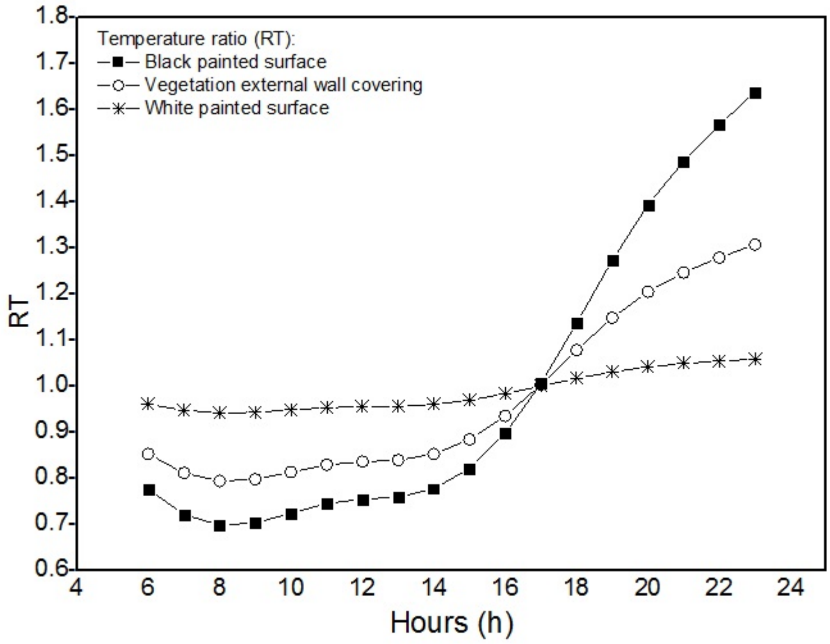

Fig. 10 Effect of wall finish on the hourly variation of the ratio RT

4.4 Effects of addition of biomass in the construction material

There is a recent tendency to use small quantities of biomass fibers mixed with mortar used for soothing wall surface prior to painting or for making finishing slabs. Using Lima (2005) experimental data reproduced in Table 1, Fig.11 was obtained, where the term "standard wall" is used to identify the wall without biomass addition. One can verify the big difference between predicted internal wall temperatures due to the addition of 10% of biomass fibers, and the corresponding time lag. These thermal properties makes construction mortar and slabs with biomass fibers excellent candidates for constructing low cost homes which have some passive thermal comfort.

Table 1 Properties of the composted mass (Lima 2005)

Slab dimensions: 230 x 114 x 64 mm	Specific mass [kg/m³]	Specific heat [kJ/kg ºC]	Thermal conductivity [W/m.ºC]	Absorptivity and Emissivity
Slab $A_{0:}$ 0% biomass fibers	1159.36	2.168	0.53	0.63 0.93
Slab $A_{10:}$ 10% biomass fibers	943.40	1.817	0.17897	0.63 0.93

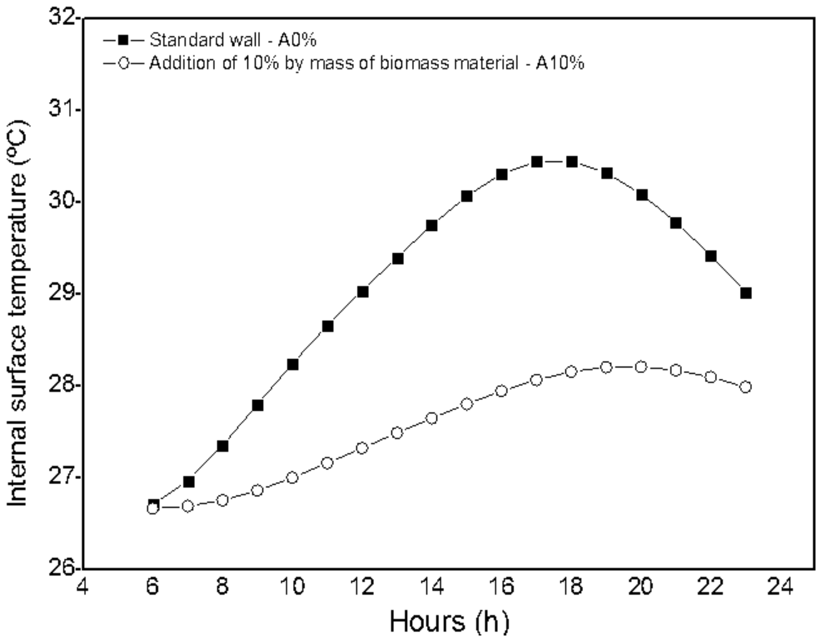

Fig. 11 Effect of biomass addition to wall material on the hourly variation of the internal surface temperature, (Lima 2005)

5. CONCLUSIONS

This paper presents a thermal model for a simple as construction element for use in thermal passive homes for low income populations. The model permits evaluating the temperature of the internal space in terms of the local solar radiation, geometrical parameters of the wall, type of external finish and local meteorological conditions. In the case of simple wall the thickness and the external finish materials (such as green wall vegetation and paints) and absorptivity were found to reduce the internal ambient peak temperature and increase the time lag. Low thermal conductivity material and surface finishing mortar mixed with dry biomass can help to reduce the solar heat gain and the internal ambient temperature.

6. ACKNOWLEDGEMENTS

The first author wishes to thank the CNPq for PQ research grant and the second author wishes to thank WIKA of Brazil Com. and Ind. Ltd. for their interest and support.

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