COMPOSITE THERMAL WALLS FOR LOW ENERGY BRAZILIAN HOMES

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ABSTRACT

The objective of this study is to investigate the behavior of thermal walls as elements in low energy consumption buildings and residences. 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. Two wall arrangements were investigated; simple wall with incorporation of external surface colour, bio mass additives to construction slabs, and double wall with and without spacing filled with stagnant air. The influence of these variations on the maximum internal ambient temperature and the corresponding time lag with respect to the maximum external surface temperature were calculated for each case. Results indicated that increasing wall thickness reduces the internal peak temperature and delays its occurrence. Light colour paints and wall planted vegetation have similar effects as increasing wall thickness. Low thermal conductivity material and use of surface finishing mortar mixed with dry biomass helps reducing the solar heat gain, internal ambient temperature and increasing the time lag. The spacing between the walls can reduce significantly the heat transferred to internal living space and increases both the thermal comfort and the temperature time lag.
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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 GHG emissions together with global energy demand and consumption. These last two generally create problems of energy distribution and severe energy demand peaks during certain hours of the day. Hence substantial governments and society 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 which have high thermal capacity and big 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 of time.

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 for and lower global energy consumption due to the load reduction/shifting.

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 can be replaced by a suitable phase change material which 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 consumed energy.

Bernard et al. [1] 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.

Ismail and Castro [2] presented the results of a numerical and experimental study of walls and roofs filled with PCM under real operational conditions to achieve passive thermal comfort. The thermal model is one-dimensional controlled by pure conduction. The numerical treatment is based on using ADI scheme and finite difference approximations. Comparison between the simulation results and the experiments indicated good agreement.

Tyagi and Buddhi [3] presented a comprehensive review of various possible methods for heating and cooling in buildings such as PCM Trombe wall, PCM wallboards, PCM shutters, PCM building blocks, 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, so that the indoor air temperature is closer to the desired temperature for a longer period of time as in, Isa et al. [4].

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. [5] proposed a concept that combines the benefits of buildings with low and high thermal mass by applying hybrid adaptable thermal storage systems and materials to a lightweight building. Calculations show 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 this type of treatment is extended to roofs and floors, as in Rostamizadeha et al. [6], Silva et al. [7], Soares et al. [8], Chou et al. [9], Guichard et al. [10] and Tokuç et al. [11].

The objective of this study is to investigate the behaviour of thermal walls as elements for low energy consumption buildings and residences. 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. Two walls arrangements are investigated; single wall with incorporations of external surface paint, bio mass additives to construction mortar, and double wall without and with spacing filled with stagnant air. The influence of these parameters on the maximum internal ambient temperature and the corresponding time lag were calculated for each case. The results showed that applying these strategies or combinations of them can increase the thermal mass of the system, reduce the temperature fluctuations in the internal ambient and reduce energy losses.

NOMENCLATURE

h	[W/m². ºC];	*Heat transfer coefficient*
ID	[MJ/m²]	Intensity of direct radiation
Id	[MJ/m²]	Intensity of diffuse radiation
Bi	[-]	Biot number
RT^*	[-]	Ratio of maximum internal temperature/Maximum external temperature
k	[W/mK]	Thermal conductivity
ρ	[kg/m³]	Specific mass
C_p	[kJ/kg ºC]	Specific heat
α_s	[m²/s]	Thermal diffusivity
α		Absorptivity
ε		Thermal emissivity
T	[ºC]	Temperature
Ts	[ºC]	Solar temperature

Subscripts

a	[m]	*Width of the external wall (first wall)*
b	[m]	Width of spacing between walls (stagnant air gap)
c	[m]	Width of the internal wall (second wall)
x	[m]	Total width of the wall
i		Regions a, b and c
AR		Atmospheric air
EXT		External ambient
INT		Internal ambient

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, constant thermo physical properties of construction material. Two wall configurations are treated in this study; simple wall with and without finishing paints and biomass additives and double wall with and without spacing filled with air. The wall configurations are shown in Figure 1.

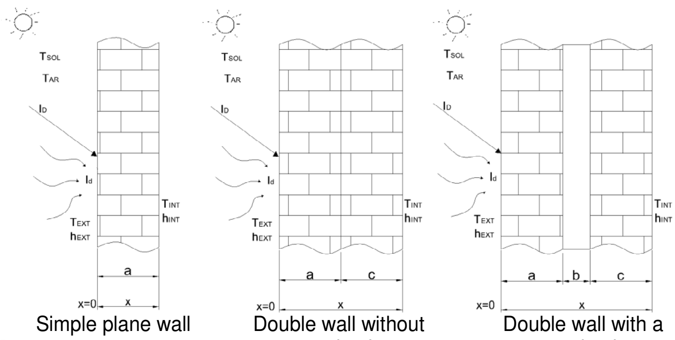

Figure 1 Geometrical details of the investigated thermal walls

The total instantaneous radiation incident over the external surface of the wall is composed of direct radiation I_D and diffuse radiation I_d. By using Hottel's method [12] 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 [13] based on meteorological data was used.

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

$$\frac{\partial^2 T_i}{\partial^2 x} = \frac{1}{\alpha_s}\frac{\partial T_i}{\partial t} \quad (1)$$

Where i = a, b, c, which refer to the external wall, spacing between the two walls and the internal wall, respectively.

The boundary condition on the external wall is as proposed by Srivastava [14], is written in the form;

$$-k_a \frac{\partial T_a}{\partial x}\bigg|_{x=0} = h_{EXT}\left[T_s - T_a\right]_{x=0} \qquad (2)$$

Where Ts is given by

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

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 calculated on a surface [MJ/m²], calculated as proposed by Hottel [19] and Liu and Jordan [20], and using available metrological data;

h_{EXT} = Coefficient of global heat transfer 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 at a specific hour of the Day calculated according to model proposed in ASHARE-Fundamentals [15] [ºC].

The boundary condition for the internal spacing, region b, we have:

$$k_a \frac{\partial T_a}{\partial x}\bigg|_{x=a^-} = k_b \frac{\partial T_b}{\partial x}\bigg|_{x=a^+} \qquad (4)$$

$$k_b \frac{\partial T_b}{\partial x}\bigg|_{x=(a+b)} = k_c \frac{\partial T_c}{\partial x}\bigg|_{x=(a+b)} \qquad (5)$$

Where

T_b = Temperature of the internal side of the wall spacing [ºC];

T_c = Temperature of the internal wall side [ºC];

The boundary condition of the internal wall, region c,

$$k_c \frac{\partial T_c}{\partial x} = h_{INT}\left[T_{c_{(x=a+b+c)}} - T_{INT}\right] \qquad (6)$$

Where

T_{INT}= Temperature of the internal ambient [ºC];

The temperature of atmospheric air (T_{AR}) at a specific hour of the day calculated according to [15], [ºC], is given by:

$$T_{AR}(t) = T_{\max} - \left(\frac{f}{100}\right)\left(T_{\max} - T_{\min}\right) \qquad (7)$$

Where T_{max}e T_{min} are the monthly average maximum and minimum temperatures obtained from the region meteorological data, and (f) is obtained from [15].

NUMERICAL TREATMENT AND VALIDATION

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 its numerical grid was optimized. The time step $\Delta\tau$ was varied in the range 0.0001 to 0.0006 s while the linear distance Δx across the wall was varied in the range of 0.02 to 0.16 m. The final values used are $\Delta\tau$ =0.0001 s and Δx =0.02 m. The graphical results were omitted for brevity.

The present model and the numerical predictions were validated against numerical and experimental measurements realized by Castro [16]. First, the numerical predictions from the present study are validated against numerical results from [16] 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 [17]. The convection heat transfer coefficients of the external side of the external wall and the internal side of the internal wall as17.03 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 [16] of the internal and external temperatures variation during the day for the case of simple wall. As can be observed, the agreement is good.

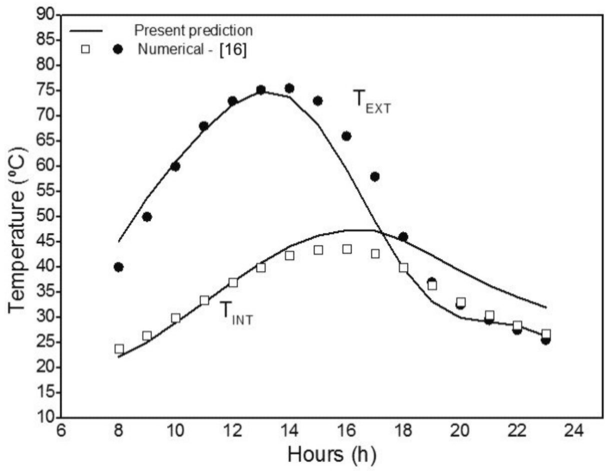

Figure 2 Comparison of the predicted (T_{INT}) and (T_{EXT}) surface temperatures with the numerical results of the simple wall from [16].

RESULTS AND DISCUSSION

A large number of numerical simulations were realized on the two configurations of thermal walls to investigate the effects wall thickness, spacing between walls, thermo physical properties of construction materials used locally, external finishing and painting of wall. The meteorological and radiation data is for the City of Campinas, Brazil. The total daily average solar radiation is 38.1 MJ/m, visibility of 12 km, monthly average maximum and minimum temperatures are 26.8 ºC and

12.8 ºC and the heat transfer coefficient on the internal side is 8.0 W/m². ºC and on the external side is 17.03 W/m². ºC.

Effectsof wall thickness

The effects of varying the wall thickness for the case of single wall are presented in Figure 3 where the thermal diffusivity was taken as $0.52x10^{-6}$ m²/s while the thermal conductivity of the wall typical material was taken as 0.7 W/m.ºC both were kept constant while the wall thickness was varied from 6 cm to 48 cm. In these simulations the value of maximum internal temperature and how it is retarded (time lag) with reference to the maximum external temperature was investigated, as in Figure 4. As can be seen increasing the wall thickness increases the wall thermal resistance and consequently reduces the heat transfer rate and the ratio of the maximum internal temperature to the maximum external temperature (RT^*) and increases the time the temperature takes to reach the surface of the internal wall (time lag).

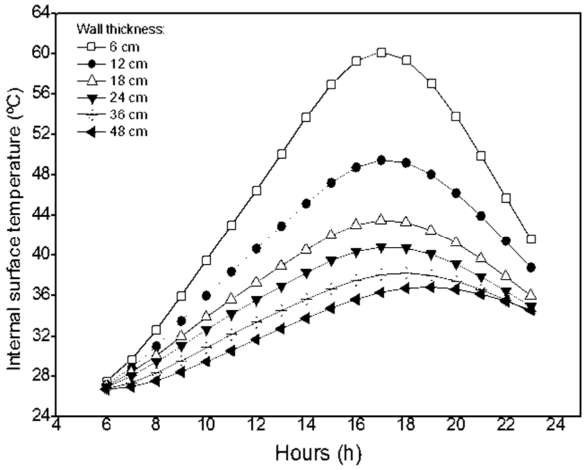

Figure 2 Variation of the internal surface temperature for different single wall thickness.

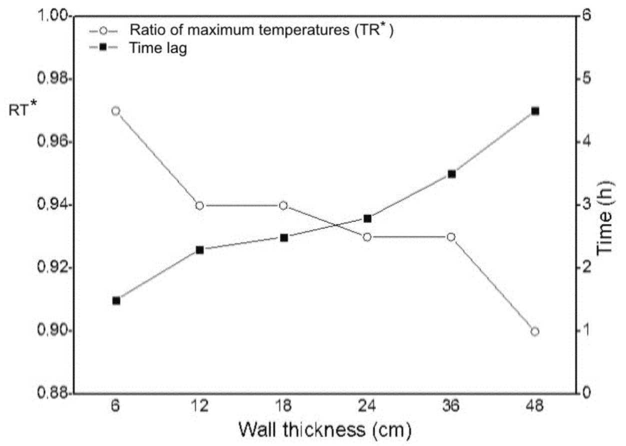

Figure 4 Variation of the ratio of maximum internal temperature and time lag for different single wall thickness.

Effects of the thermal conductivity of construction materials

The simulations were realized to investigate the effects of varying the thermal conductivity of the construction materials where the wall thickness was 10 cm, specific mass of the bricks is 1600 kg/m³, specific heat of 0.92 kJ/kg ºC, absorbance of 0.63 and emissivity 0.93, Çengel, [17] while the thermal conductivity was varied from 0.1 to 0.9 W/m.ºC. As can be seen from Figure 5 the decrease of the thermal conductivity of the material increases its thermal resistance and reduces the ratio of the maximum internal temperature to the maximum external temperature and increases the time lag. Typical construction material has relatively high thermal conductivity in the range from 0.65 to 1.3 W/m.ºC.

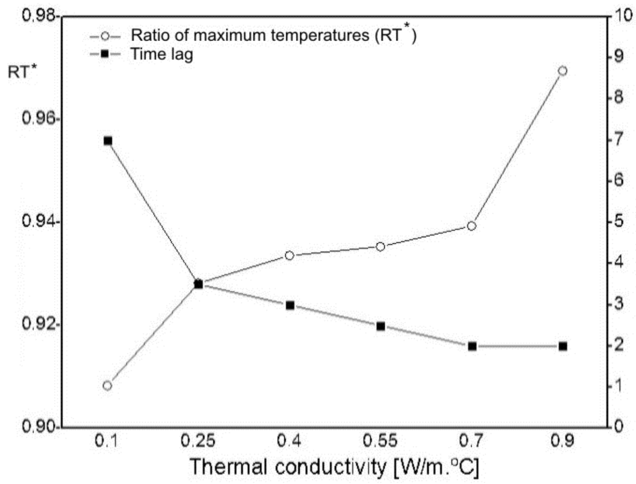

Figure 5 Effect of the material thermal conductivity on the ratio RT^* and time lag for the case of single wall.

Effects of the wall finishing material of the external surface

The effects of the external wall surface finishing material, that is, emissivity and absorptivity on the value of the maximum internal temperature and the corresponding time lag. The simulations were realized for wall thickness of 12 cm and thermal conductivity of the bricks of 0.9 W/m.ºC and the other properties as in the preceding case except that the emissivity and absorptivity were varied using values from Çengel [17] e ASHRAE [15]. As can be seen from Figure 6 black painted wall absorbs solar radiation and therefore is adequate for ambient heating applications. The white painted wall on the other hand absorbs little amount of incident energy and is suitable for cooling ambient applications. Wall covered with natural vegetation wall covering has a moderate performance with temperature profile between the two wall paints.

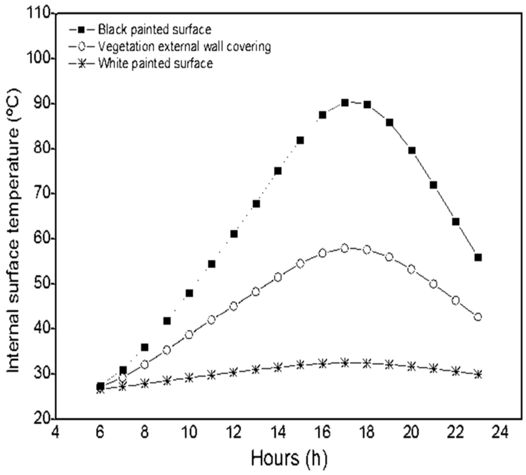

Figure 3 Hourly variation of the internal surface temperature with the type of finish material for the case of single wall.

Effects of addition of biomass in the construction material

There is a recent tendency to use small quantities of biomass fibres mixed with mortar used for soothing wall surface prior to painting or for manufacturing slabs. Using the experimental data from [18] for flat slabs of dimensions 230 x 114 x 64 mm reproduced in Table 1, Figure 7 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 fibres, and the corresponding time lag. These thermal properties makes construction mortar and slabs with biomass fibres excellent candidates for constructing low cost homes which have some passive thermal comfort.

Table 1 Properties of the composted mass [18].

Slab dimensions:	ρ [kg/m³]	C_p [kJ/kg ºC]	k [W/m.ºC]	α and ε
Slab A_{0}: 0% biomassfibres	1159.36	2.168	0.53	0.63 0.93
Slab A_{10}: 10% biomassfibres	943.40	1.817	0.17897	0.63 0.93

Effects of the spacing between the two walls

In the case of double wall,the spacing between the walls containing ambient air was varied from 0 to 20 mm. Again for this case, simulations were realized to investigate the effects of spacing width. The simulations were realized for two parallel walls of 12 cm thickness each with spacing in between them. The walls are manufactured from commercial bricks of thermal conductivity of 0.7 W/m.ºC, specific mass of 1600 kg/m³, specific heat of 0.84 kJ/kg ºC, absorptivity of 0.63 and emissivity of 0,93. The spacing between the two walls contain air of thermal conductivity of 0.025 W/m.ºC, specific mass of 1.184 kg/m³ and specific heat of 1 kJ/kg ºC.

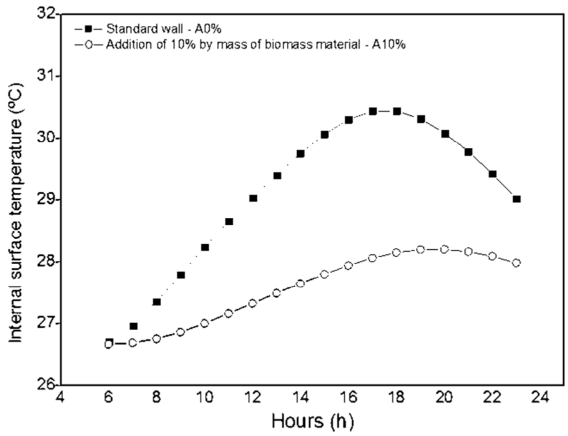

Figure 7 Effect of biomass addition to mortar material on the internal surface temperature for the case of single wall.

Figure8 shows effects of increasing the width of the spacing between walls for the case of double wall arrangement on the variation of the internal temperature. As can be seen a spacing of 20 mm keeps a constant internal temperature independent of the variation of the external ambient temperature because of the high thermal resistance of the wide air gap.

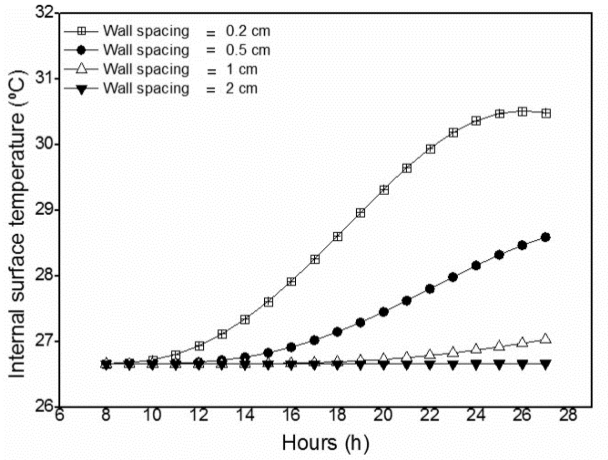

Figure 8 Effect of wall spacing on the internal wall temperature for the case of double wall.

Comparison between simple and composite walls

Figure9 shows the temperature profiles of the internal wall for double wall without spacing and double wall with 20 mm spacing as compared with the case of single wall. One can observe the remarkable difference between the internal temperature profiles of the double wall with air layer of 20 mm and the other two walls. The internal wall temperature remains unchanged along the day due to the additional thermal resistance of the air layer acting as a thermal shield against penetration of heat across the wall.

CONCLUSION

Two wall configurations were investigated in this paper; single wall and double wall with a gap in between. In the case of single wall the thickness and the external finish materials such as green wall vegetation and paints, specifically absorptivity and emissivity 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. The spacing between the walls with trapped air mass works as an efficient low cost insulating material and can reduce significantly the heat transferred to internal living space.

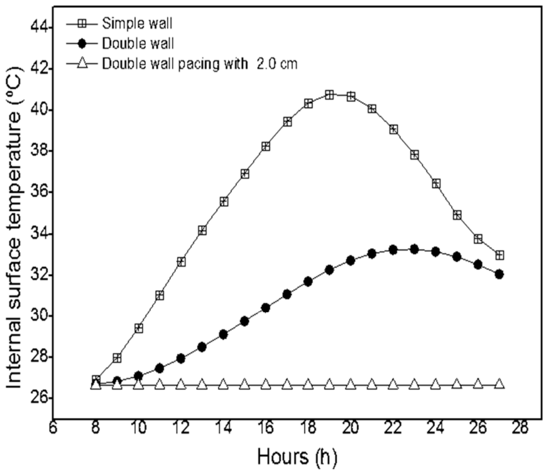

Figure 9 Variation of the internal surface temperature as function of the geometry of the wall.

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