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Numerical Modeling of Composite Thermal Walls

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Abstract: Thermal comfort in buildings, offices and residences is of extreme importance especially in very cold and very hot regions. Usually this mismatch between the human necessities and the ambient conditions was solved by artificial heating and cooling where fossil based energy is used to accomplish this desired comfort. This practice led serious problems of energy generation, distribution, ambient degradation where the heating and cooling shares reached unsustainable levels. It is for these reasons, in last few decades, more technical and political attentions were devoted to keep this problem under tight control. The correct modeling of walls used in buildings and their construction elements promote greater energy efficiency and thermal comfort to users.

Many numerical, theoretical and experimental studies were realized with the objective of reducing the use of air conditioning systems and heating systems or preferably eliminating this necessity by adequate design of the building and using thermally efficient elements in the construction. The main objective of this work is to investigate composite thermal walls and their possible impact on thermal comfort during summer and winter seasons in Campinas, São Paulo, Brazil. The investigation includes analyzing the effects of varying the wall thickness and thermo-physical properties of building materials. The mathematical model is based on one dimensional transient formulation, both the model and the boundary conditions were discretized using finite difference scheme. Numerical tests were realized to make the results independent of the grid size and the time step. Simulations were then performed on a simple wall considering conventional materials locally used in construction of residences, the geographical and climatic aspect of the place. The results indicated that materials with insulating characteristics, low thermal conductivity, low solar absorptivity and thicker walls can retard the heat flow into the buildings and reduce and shift the maximum temperature in the interior of the building. Three models of different thermal walls analyzed. The model is composed of a flat surface subjected to solar radiation, convection on external surface and conduction through the walls and convection on the internal wall. From the numerical simulations, it was possible to determine the temperature distribution curves through the wall, the internal and external temperature variation, the internal peak temperature and its time lag behind the external peak temperature. The results confirm that beneficial effects can be achieved by using composite walls.

Key words: thermal walls, passive thermal comfort, low energy dwellings, modeling of thermal walls

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 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.

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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. Further economic analysis indicated that the concept could effectively help in reducing the electric energy consumption, improve the energy demand pattern and reduce greenhouse emissions.

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 Zhu et al. [4], Isa et al. [5] and Kuznik et al. [6].

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. [7] 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. [8], Silva et al. [9], Soares et al. [10] and Faraji et al. [11], Alqallaf and Alawadhi [12], Chou et al. [13], Guichard et al. [14] and Tokuc et al. [15].

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. Three thermal walls were investigated; simple wall used as reference wall, simple wall with incorporations of external surface color, bio mass additives to construction blocks, and finally double wall, double wall with 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. 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

a = Width of the external wall (first wall);

b = Width of spacing between walls (stagnant air gap);

c = Width of the internal wall (second wall);

i = regions a, b and c;

x = Total width of the wall;

hEXT = Heat transfer coefficient of the external ambient (W/m². °C);

hINT = Heat transfer coefficient of the internal ambient (W/m². °C);

ID = Intensity of direct radiation;

Id = Intensity of diffuse radiation;

RT = Ratio of maximum internal temperature/ Maximum external temperature

TAR = Temperature of atmospheric air;

TEXT = Temperature of the external ambient;

TINT = Temperature of the internal ambient;

Ti = Temperature of region i;

T_S = Solar temperature, (°C).

2. Analysis and Modelling

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. Three wall configurations are treated in this study; i) simple plane wall, ii) Double wall without spacing in between and iii) Double wall with a spacing in between.

The total instantaneous radiation incident over the external surface of the wall is composed of direct radiation ID and diffuse radiation Id. By using Hottel's method [16] 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 [17] 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;

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

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 [18], is written in the form;

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

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

Ts = Solar temperature [°C];

ΔR = Difference between incident solar radiation over the surface and radiation emitted by a Black body at the temperature of atmospheric air (kJ/m^2 h).

ka = Thermal conductivity of the external wall (W/m.°C);

αs = Thermal diffusivity of the external wall (m^2/s);

Qs(t) = Intensity of incident solar radiation calculated on a surface (MJ/m^2), calculated as proposed by Hottel [16] and Liu and Jordan [17], and using available metrological data;

hEXT = Coefficient of global heat transfer between the external surface and external air (W/m^2.°C);

Ta = Temperature of the external side of the wall (°C);

TAR = Temperature of the external atmospheric air at a specific hour of the Day calculated according to model proposed in ASHARE-Fundamentals [19] (°C).

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

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

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

Where

Tb = Temperature of the internal side of the wall spacing (°C);

Tc = Temperature of the internal wall side (°C);

The boundary condition of the internal wall, region c,

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

Where

TINT = Temperature of the internal ambient (°C);

The temperature of atmospheric air (TAR) at a specific hour of the day calculated according to ASHARE-Fundamentals [19], (°C), is given by

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

Where Tmax e Tmin 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.

2.1 Numerical Treatment

In order to solve the governing equations and the associated boundary conditions the finite difference scheme and explicit formulation scheme were used to discretize the equations.

A numerical program in C was developed and tested according the block diagram showed earlier. The time step was varied in the range 0.0001 to 0.0006 second while the linear distance across the wall was varied in the range of 0.02 to 0.16 m. A coarse grid was used across the masonry wall (4 grid points) and a fine grid was used in the spacing between the two walls (10 grid points).

3. Results and Discussion

A large number of numerical simulations were realized on the three configurations of thermal walls to investigate the effects wall thickness, spacing between walls and thermos-physical properties of construction materials used locally. 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°C and 12.8°C and the heat transfer coefficient on the internal side is 8.0 W/m^2.°C and on the external side is 17.03 W/m^2.°C.

3.1 Effect of Varying Wall Thickness

The effects of varying the wall thickness are presented in Figs. 1 and 2, where the thermal diffusivity was taken as 0.52×10-6 m^2/s while the thermal conductivity of the wall typical material was taken as 0.7 W/m.°C both were kept constant while the wall thickness was varied from 6 cm to 48 cm. In these simulations we were interested in finding the value of maximum internal temperature and how it is retarded (time lag expressed in hours) with reference to the maximum external temperature. As can be seen increasing the wall thickness increases the wall thermal resistance and consequently reduces the penetrating heat transfer rate and the ratio of the maximum internal temperature (RT) and increases the time to reach the internal wall surface (time lag).

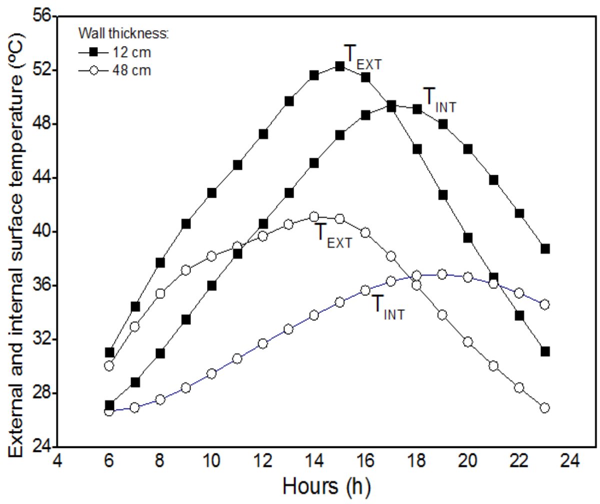

Fig. 1 Variation of external and internal surface temperature for different wall thicknesses.

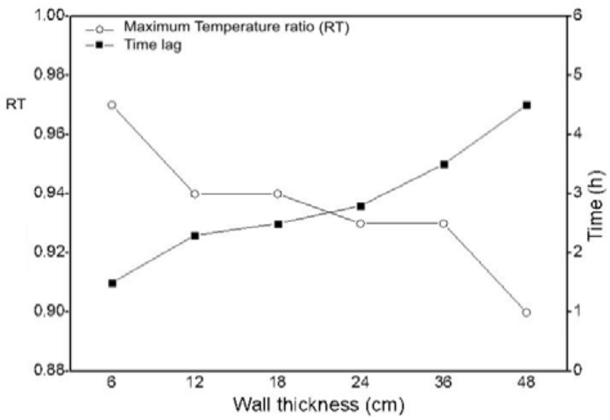

Fig. 2 Variation of the ratio of maximum internal temperature and time lag for different walls thickness.

3.2 Effects of Varying 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/m^3, specific heat of 0.92 kJ/kg°C, absorptivity of 0.63 and emissivity 0.93, Çengel [20], while the thermal conductivity was varied from 0.1 to 0.9 W/m.°C. As can be seen from Fig. 3 the decrease of the thermal material conductivity increases its thermal resistance and reduces the peak 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.°C.

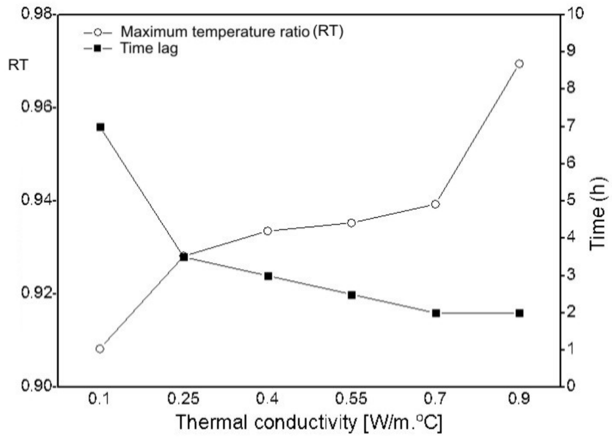

Fig. 3 Effect of the material thermal conductivity on the ratio of maximum internal temperature and time lag.

3.3 Effect of the Spacing between the Two Walls

The variation of the width of the spacing showed very little effect on the external wall temperature. This causes a slight increase in temperature due the increase of the thermal resistance of the wall which helps to store a little more heat in the bulk mass.

Fig. 4 shows effects of increasing the width of the spacing between walls on the temperature 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.

3.4 Comparison between Simple and Composite Walls

Fig. 5 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 simple 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.

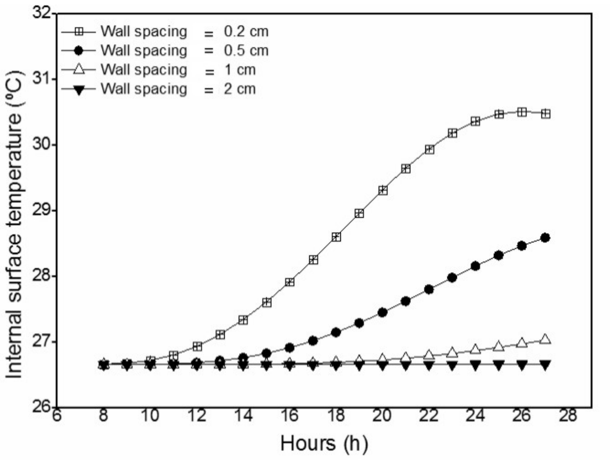

Fig. 4 Effect of varying the gap between walls on the hourly temperature variation of the internal wall surface.

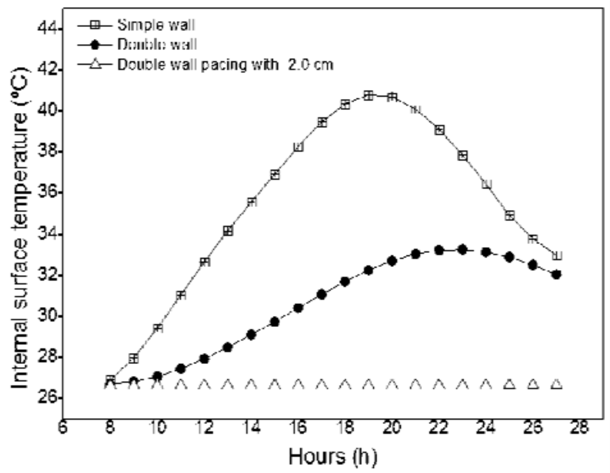

Fig. 5 Variation of the internal surface temperature as function of the geometry of the wall.

4. Conclusions

This paper presents a thermal model for simple and double wall as a thermal construction element for use in thermal passive homes. The model permits evaluating the temperature of the internal space in terms of the local solar radiation, geometrical parameters of the wall type and local meteorological conditions.

Three configurations were investigated; simple wall; double wall without spacing and double wall with spacing between the two walls. In the case of simple wall, the wall thickness is found to control the internal ambient peak temperature and its lag time.

Low thermal conductivity construction materials can help to reduce the solar heat gain.

The most important parameter in the double wall is the spacing between them where the air mass as an efficient low cost insulating material and reduce significantly the heat transferred to internal living space.

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