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Modeling And Experimentation Of PCM Double Glass Windows

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Abstract

Windows are essential elements for the building esthetic aspect while permitting contact with the external ambient but contribute much to the thermal losses and solar heat gain. The recent tendencies to reduce wastes, preservation of the ambient and conservation of energy, urged research efforts to enhance window thermal performance while maintain the esthetic aspect of the building and minimize the solar heat gain. One viable technique is to use PCM as thermal insulation filler that increases the thermal inertia of the window. In the present study, the transmissivity, reflectivity and absorptivity of commercial glass sheets were determined experimentally. The double glass PCM window model is based on the enthalpy approach and one dimensional heat conduction model in the PCM. Finite difference approximation and both fixed and moving grids were used in the numerical treatment of the glass and PCM, respectively. Additional numerical and experimental results were presented and discussed.

Keywords: *PCM Double Glass Windows, Passive Thermal Comfort, Solar Heat Gain, Energy Reduction in Buildings.*

1. Introduction

Thermal storage plays an important role in energy conservation of a building, and is greatly assisted by the incorporation of phase change materials, PCM, in building components. Latent heat storage in a phase change material is very attractive because of its high storage density with small temperature swing. It has been demonstrated that for the development of a latent heat storage system in a building fabric, the choice of the PCM plays an important role in addition to heat transfer mechanism in the PCM.

Thermal energy storing walls, roofs, ceiling and floors of buildings may be enhanced by encapsulating or embedding suitable PCMs within their 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.

Buildings components and systems using PCM have been recognized as advanced energy technologies in enhancing energy efficiency and sustainability of buildings as it provides better indoor thermal comfort because of the reduced indoor temperature fluctuations, and lower global energy consumption due to the load reduction/shifting.

Windows are essential components of a building permitting contact between the occupants and the exterior ambient but they represent the weak link between the external ambient and the conditioned internal space. Many studies were dedicated to alleviate their contribution to the discomfort and energy losses of buildings. To enhance their thermal performance, low emissivity films, paints or spectrally selective films are used.

Other techniques employ low conductivity gases such as Argon and Helium instead of stagnant air in double glass windows, double glass windows filled with infrared absorbing gases, double glass windows with natural and forced ventilation and glass windows employing one or more of these techniques. Other alternative solutions were investigated including double and triple glass windows, windows with PCM shutters, PCM curtains, and windows filled with PCM, silica aero gel etc.

To reduce the windows drawbacks from the thermal point of view, some studies proposed viable solutions such as the use of reversible windows, filling the spacing between glass sheets by silica aero gel, PCM and thermal radiation absorbing gases as reported in [1, 2, 3].

Nielsen et al. [4] reported the results of a study to enable comparing easily the energy performance of different glazing or windows. They used for this objective developed diagrams which give the net energy gain based on the orientation, the tilt and the U-value of the glazing or windows.

Fang [5] presented the results of a study focusing on the U-factor of a window with a cloth indoor curtain. The corrected empirical equations can be easily used to estimate the U-factor of a practical window with a cloth curtain.

Ismail and Henriquez [6] reported the results of a numerical and experimental study on thermally efficient windows. The number of glass sheets, their thickness and the gap between them were investigated and the results were compared with experimental measurements and reasonably good agreement was found.

Perez-Grande et al. [7] presented the results of a study of the influence of glass properties on the performance of double-glazed facades while Weinlader et al. [8] used double glazing combined with phase change materials in day lighting elements. Compared to a double glazing without PCM, a facade panel with PCM showed about 30% less heat losses in south oriented facades. Solar heat gains are also reduced by about 50%.

Coupled radiation and natural convection heat transfer occurs in vertical enclosures with walls at different temperatures filled with gas media. In glass double window, the thermal insulation in hot climates by using infrared absorbing gases appears as a viable alternative to improve their thermal performance.

Ismail and Salinas [9] analyzed the coupled radiation and natural convection heat transfer occurring in glass windows filled with non-gray absorbing gases. The temperatures distributions in the gas and the glass domain are computed and the thermal performance of the gas mixtures is evaluated and discussed.

Ismail and Henriquez [10] presented the results of a study on a ventilated double glass window with forced air flow. The proposed model is one dimensional and unsteady based upon global energy balance over the glass sheets and the flowing fluid. The results show that the effect of the increase of the mass flow rate is found to reduce the mean solar heat gain and the shading coefficients while the increase of the fluid entry temperature is found to deteriorate the window thermal performance.

In the building facade, window glazing is one major element contributing to the space thermal load. Lots of work has been done on developing advanced glazing systems that are energy efficient under various climatic conditions as in [11, 12, 13, 14, 15, 16].

Filling the gap between glass sheets with infrared absorbing gas appears, as shown before, is a solution for thermally insulated glass windows. Fluid flow of water or air in the gap between the glass sheets can reduce the amount of heat transferred to the interior space and hence reduce the cooling load reducing marginally natural illumination. The flow between the glass sheets can be natural or forced and the heated fluid can be used directly or stored for later use. Other investigations dedicated to different aspects of double glass windows performance covering a variety of techniques are reported in [17, 18, 19, 20, 21].

A significant amount of solar heat gain in buildings comes through the windows, and an effective way to reduce it is to install exterior shading devices, such as window shutters. Alawadhi [22] investigated numerically a technique of solar heat gain reduction in building through windows using phase change material (PCM) in the shutter. The results indicate that the heat gain through windows can be reduced by about 23.3%.

Carlos et al. [23] reported the results of a study on ventilated double window, as a passive heating system, acts as a heat reclaiming device. Part of the heat loss from inside through the window is returned back to the room by the air flow, acting as a heat recovery system.

In building envelopes, windows are considered as a weak heat link due to their low thermal resistance, transparency to solar radiation and hence responsible for a large portion of solar heat gain in buildings. Wang and Zhao [24] presented a low cost technique using a window with a PCM internal curtain to reduce the solar heat gain in hot summers. It is found that the average heat transfer rate into the indoor space can be reduced by as much as 30.9%.

Goia et al. [25] provided the results and data set of luminous and solar properties of glazing units with PCMs in gaps. The transmissivity, reflectivity and absorptivity spectra of double glazing units characterized by different PCM layer thicknesses in the gap are reported.

The present study presents a model for the PCM double glass window based on the enthalpy approach and one dimension heat conduction in the PCM. Finite difference approximation and both fixed and moving grids were used in the numerical treatment for the glass sheets and PCM, respectively. The model was solved numerically and the results were validated against experimental results showing reasonably good agreement.

2. Double glass window with PCM

The concept of double glass window with PCM is relatively simple and thermally effective, usually formed of double glass sheets separated by a gap filled with a PCM of certain fusion temperature. In operation the external glass receives the solar radiation, where part of it is absorbed, part is reflected and the rest, about 80 %, is transmitted to the PCM region (initially in the solid phase). The PCM layer absorbs part of the energy received, transmits a small and reflects the rest. At the boundary surface between the external glass sheet and PCM, the radiation absorbed by the PCM and the heat conducted by the glass surface raise the PCM temperature converting the adjacent layer to the glass surface into liquid PCM. This process continues until all the PCM changes to liquid and consequently the internal room temperature starts to change. A well designed window project will ensure that the external temperature will start to decline before the total fusion of the enclosed PCM.

2.1 PCM used in windows

The PCM used in this application must be safe to handle, stable and relatively cheap. From the available options it was decided to use polyethylene glycol (available in the laboratory at the time and fairly cheap) and known commercially as ATPEG or simply PEG. We used the PCM as PEG 600 whose fusion temperature range is 21-23 ºC which is the temperature range for this study. For this product additional tests were realized to determine the latent heat of fusion and the specific heat by using DSC calorimetry.

The specific mass of the mixture was determined by measuring the mass and volume at different temperatures in the case of the liquid phase. The solid phase is found to have a specific mass of 1135.4 ± 0.001 kg/m^3 at temperature 20 ºC. The thermal conductivity is measured by the hot cup type apparatus for the determination of thermal conductivity of liquids. The thermal conductivity at 40 ºC is found to be 0.53 ± 0.01 W/mK.

Table 1: Margin specifications

$HO(C_2H_4O)_{12}\ C_2H_4OH$	
Fusion temperature	296 ± 1 K
Latent heat of fusion	127.3 ± 0.01 kJ/kg K
Specific heat of the liquid phase at 25°C	2.05 ± 0.002 kJ/kg
Specific mass of the liquid phase at 25°C	1123 ± 0.001 kg/m^3
Viscosity of the liquid phase at 38°C	0.081 ± 0.0001kg/m s
Average molecular weight	600 g/mol

2.2 Experimental evaluation of optical properties of glass sheets

Glass sheets used in windows are commercial products and generally, their optical properties such as reflectivity, absorptivity and transmissivity are not available. In the present study, we used arrangements and glass configurations made of commercial glass sheets. Hence, it is essential to characterize optically the glass configurations that will be investigated.

The standard ASTM-E424-71 indicates two methods that can be used to determine the transmissivity and reflectivity of materials in the form of sheets. In the present study, we used the spectrophotometer with integrating sphere for measuring the transmissivity and reflectivity. The spectrophotometer used is from Perkin-Elmer Lamp 9 in the range of wave length of 300-2800 nm to cover the range of interest. The transmissivity values are referred to air while the reflectivity values are referred to standard film of Magnesium oxide (MgO).

Evaluation of transmissivity

The optical transmissivity was determined for commercial simple glass sheets of thickness varying from 3mm to 8 mm. As can be seen from Fig.1 the increase of thickness reduces the transmissivity of these glass sheets.

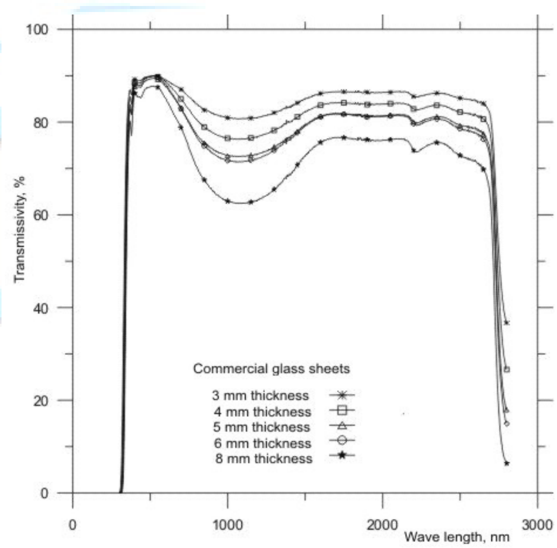


Fig.1 Variation of transmissivity with glass thickness for simple glass panels.

To investigate the effect of spacing between glass sheets filled with air, experiments were realized on double glass sheets of different thicknesses varying between 3mm-8mm but with a fixed spacing of 3mm filled with air. Fig. 2 indicates a reduction of transmissivity with the increase of the sandwich thickness in the infra red range.

To investigate the effect of the PCM and its thickness on radiation transmissivity, experiments were realized for PCM thickness varying from 3mm to 20mm placed in between glass sheets of 6mm thickness. Fig. 3 indicates a substantial reduction in the transmissivity in the infra red range. It is believed that the PCM color can have effect on the transmissivity only in the visible range. Experiments were realized on Colorless, green and blue PCM, as shown in Fig 4, which does not show any noticeable variation due to color of the PCM except in the visible range.

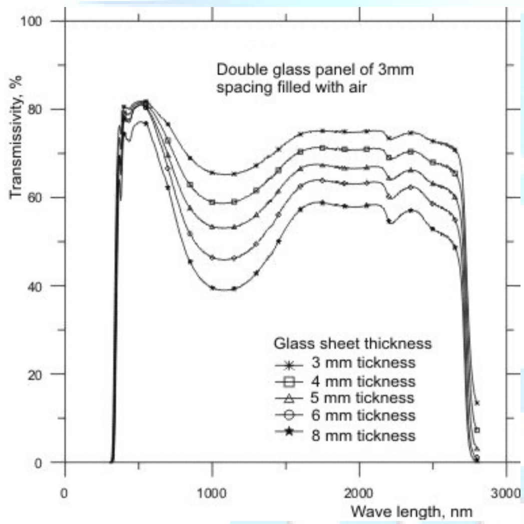


Fig. 2 Variation of transmissivity with the glass thickness for double glass panel of 3 mm spacing filled with air.

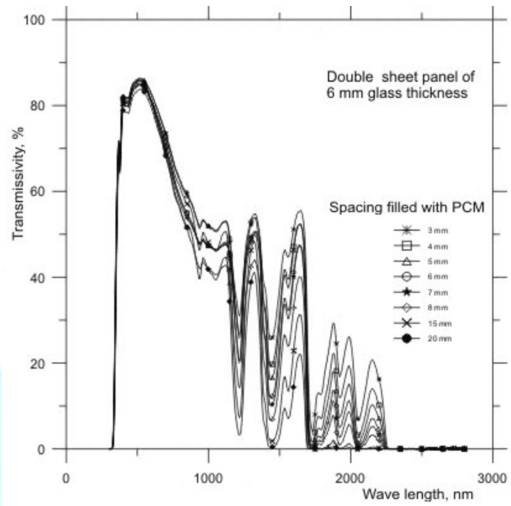


Fig. 3 Variation of transmissivity with the glass thickness for double glass panel of 6 mm spacing filled with PCM.

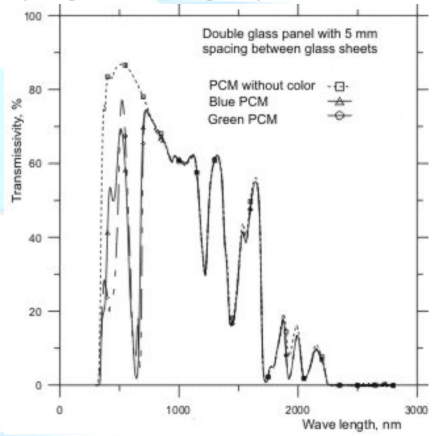


Fig. 4 Variation of transmissivity with the glass thickness for double glass panel of 5 mm spacing filled with colored PCM.

Evaluation of reflectivity

Reflectivity tests were realized to complete the characterization of the glass sheets used in this investigation. Fig. 5 shows the results of simple glass sheet of 3mm thickness. As can be seen the reflectivity is around 13% over the whole wavelength range.

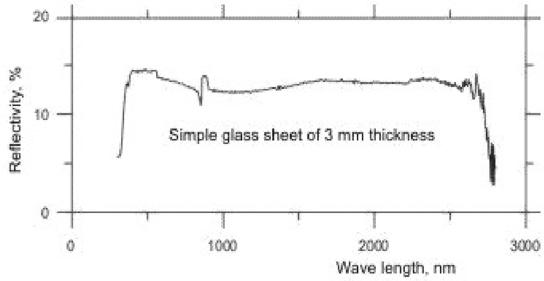


Fig. 5 Variation of reflectivity with wave length for a simple glass panel of 3 mm glass thickness.

Fig. 6 shows the transmissivity results for double glass panel of 3mm thickness with spacing of 3mm filled with air. As can be seen, the reflectivity is about glass 16%. For double panel with glass sheet thickness of 6 mm filled with PCM the reflectivity was only about 7% as shown in Fig. 7.

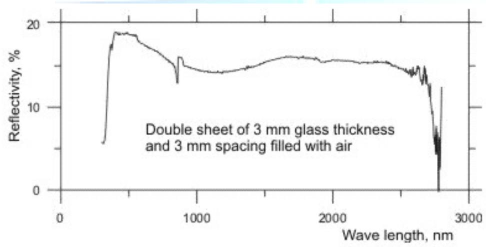


Fig. 6 Variation of reflectivity with wave length for double glass panel of 3 mm glass thickness and 3 mm spacing filled with air.

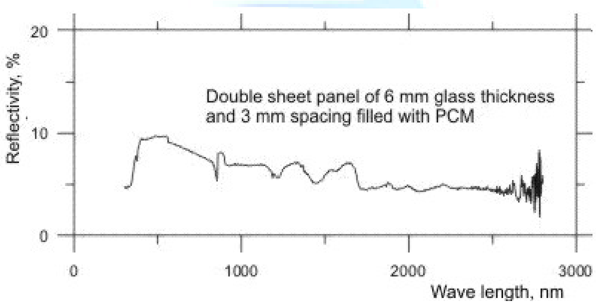


Fig.7 Variation of reflectivity with wave length for double glass panel of 6 mm glass thickness and 3 mm spacing filled with PCM.

Evaluation of absorptivity

The measured transmissivity and reflectivity of simple and double glass configurations were used to determine the corresponding absorptivity for each configuration. Fig. 8 shows the absorptivity result for the case of simple glass sheet of 3mm thickness.

Fig. 9 shows the results for the case double glass panel of 6 mm glass thickness and 3 mm spacing filled with air. One can verify the increase of absorptivity in comparison with the case of simple glass sheet. When the same glass specimen is filled with PCM the absorptivity is found to increase in the wave length range 750 to 1750 nm as can be seen in Fig. 10.

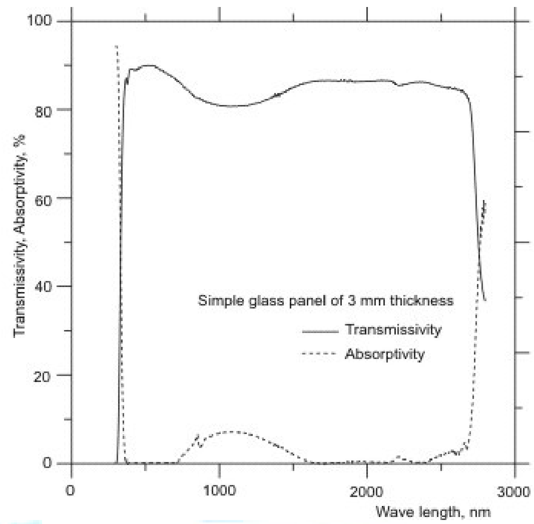


Fig. 8 Variation of transmissivity and absorptivity of simple glass panel of 3 mm glass thickness.

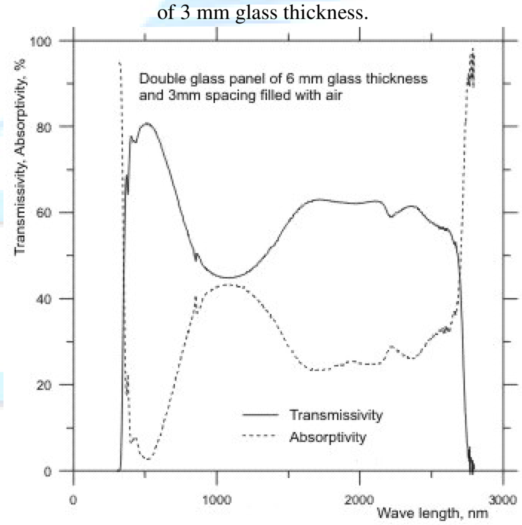


Fig. 9 Variation of transmissivity and absorptivity of double glass panel 6 mm glass thickness and 3 mm spacing filled with air.

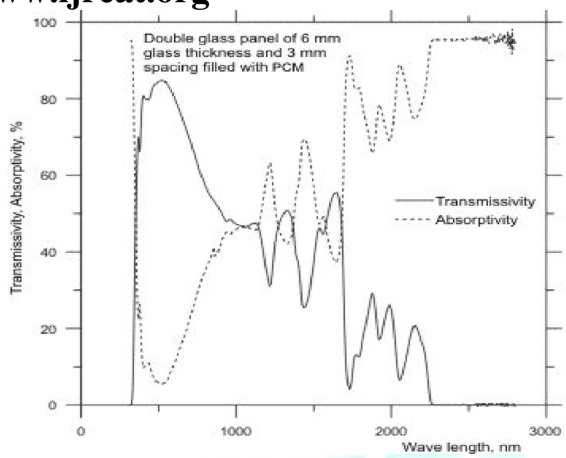


Fig. 10 Variation of transmissivity and absorptivity of double glass panel 6 mm glass thickness and 3 mm spacing filled with PCM.

2.3 Evaluation of transmitted energy

From the measured transmission values of the different glass configurations the net energy transmitted through each glass combination is evaluated. In this evaluation the normal incident radiation is used together with the measured transmission values to determine the energy incident in each wave length range. The incident energy in each range of wave length is integrated to obtain the percentage of incident energy.

The energy transmitted in the case of simple glass sheet of 3 mm thickness in function of wave length calculated by this procedure is shown in Fig.11. Similar calculations were realized for each glass thickness that is 4, 5, 6, 8 mm.

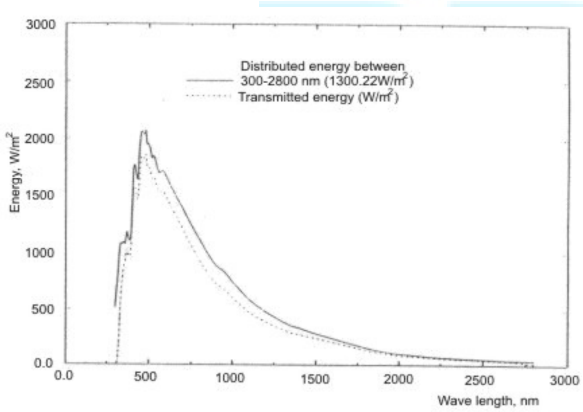


Fig.11 Energy transmitted through a simple glass panel of 3 mm thickness.

The corresponding curves were omitted for brevity. Fig. 12 shows the variation of the percentage normal transmitted energy with the glass thickness for common single glass sheets. As expected the transmitted energy is reduced when the thickness is increased.

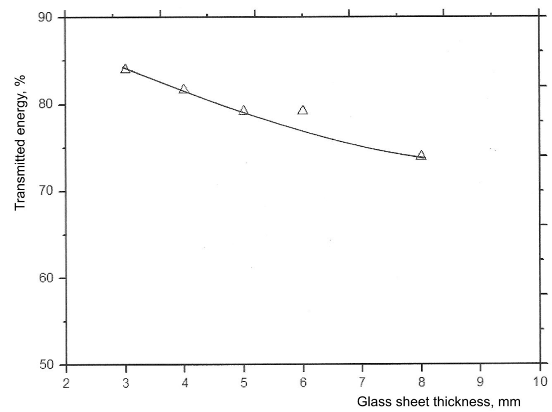


Fig.12 Effect of thickness variation on the fraction of transmitted energy through commercial glass sheets.

The same treatment was done for the cases of double glass configuration of different glass sheet thickness but separated by a fixed spacing of 3 mm filled with air. Fig. 13 shows a typical result and the rest are omitted for brevity.

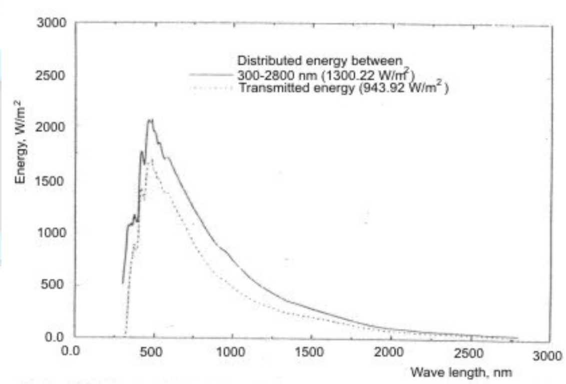


Fig.13 Energy transmitted through a double glass panel of 3 mm glass thickness and 3 mm spacing filled with air.

Fig.14 shows the variation of the transmitted energy as function of the thickness of the glass thickness, while Fig. 15 shows a comparison of the energy transmitted due to simple and composite configurations of the same glass sheets.

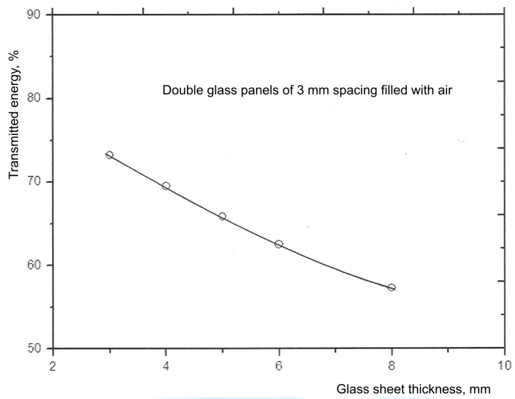


Fig 14 Variation of the fraction of transmitted energy of double glass panels filled with air due to variation of glass thickness.

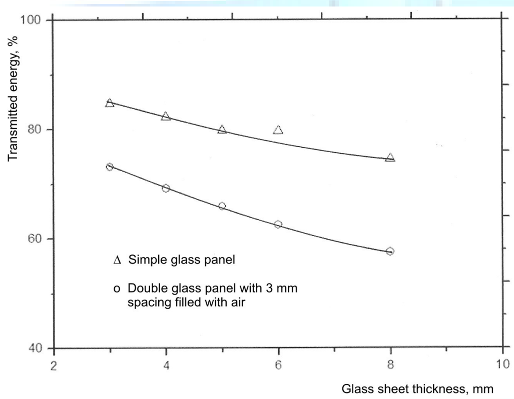


Fig 15 Comparison of the fraction of transmitted energy of simple and double glass panels.

The effect of varying the spacing between the glass sheets of constant thickness of 6 mm is investigated using the same procedure as before. The spacing filled with air was varied from 3mm to 8 mm. Fig. 16 shows that increasing the spacing between the glass sheets reduces the transmitted energy.

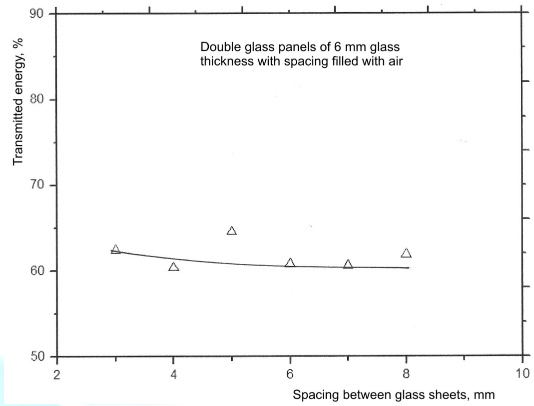


Fig 16 Fraction of transmitted energy of double glass panels with spacing filled with air.

The case of double glass of 6mm thickness having spacing varying from 3 mm to 20 mm filled with PCM was treated in a similar manner and the results are presented in Fig. 17 indicating good reduction in the transmitted energy as a result of the increase of the PCM layer.

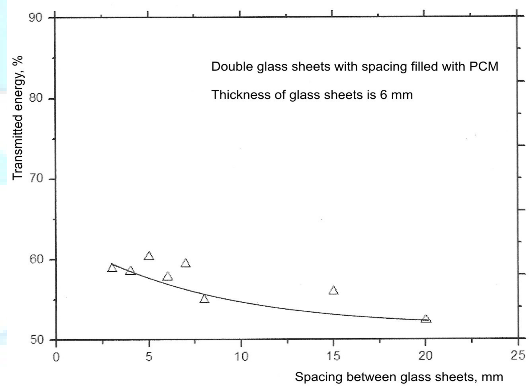


Fig 17 Fraction of transmitted energy of double glass panels with spacing filled with PCM.

It is important to mention that in the above analysis the incident radiation was considered normal to the glass surface and hence the results should be considered as maximum values. In the real situation the incident radiation is inclined with respect to glass surface and this causes more reduction of transmitted energy. Also it is important to remember that the effects presented are solely due to the variation of transmissivity. Possible reflection and absorptivity effects may cause more reduction of transmitted energy.

3. Formulation of double glass window with incorporated PCM

The concept of the PCM double glass window is relatively simple and effective. It is composed of double glass with a gap between the glass sheets filled with PCM of certain melting temperature as in Fig.18. The mode of operation is as follows. The external glass receives the solar radiation, where part of it is absorbed, another part is reflected and the rest, about 80 %, is transmitted to the PCM layer (initially in the solid phase). At the interface between the external glass sheet and PCM, the radiation absorbed by the PCM and the heat conducted by the glass surface raise the PCM temperature and melt a layer of the PCM. This process continues until all the PCM is in the liquid phase. Starting from this instant any additional heat received by the PCM will cause a corresponding increase of the liquid PCM and consequently the indoor temperature. A well designed project will ensure that the external temperature will start to decline before the total melting of the enclosed PCM.

Scheme of the double glass window with gap filled with PCM is shown in Fig. 18. As can be seen, the thickness of the external glass is (a) and that of the internal glass is (c) while the PCM spacing is (b). The incident solar radiation on external window has intensity of Io (W/m^2), part of it is reflected and part is absorbed by the glass sheet and the rest is transmitted to the PCM layer. The radiation reaching the PCM layer mostly will be used for melting a layer of PCM while the radiation in the visible range will penetrate through the second glass to the internal ambient. The interface between the solid and liquid phases of the PCM and the temperatures at the different faces of internal and external glass sheets as well as in the PCM regions are indicated below.

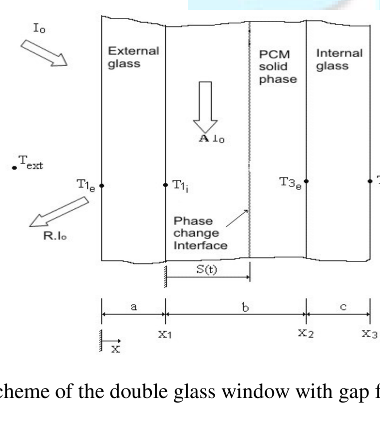


Fig.18 Scheme of the double glass window with gap filled with PCM.

To formulate the problem, consider that there is no convection in the liquid phase of the PCM and constant physical and thermal properties. Also adopt one dimensional formulation and ignore the effects of the extremities of the glass panel.

The differential equation for each region is

$$\frac{\partial T_i}{\partial t} = \alpha_i \frac{\partial^2 T_i}{\partial x^2} - \frac{1}{\rho_i C_i}\frac{\partial I}{\partial x} \qquad (16)$$

where i = 1, 2, 3 represents the external glass, PCM and internal glass respectively.

The appropriate boundary conditions for the three regions are:

a) The boundary condition at x = 0 is determined by the condition that the external surface of window exchanges heat by convection and radiation with the external ambient

$$-k_1 \left.\frac{\partial T_1}{\partial x}\right|_{x=0} = h_{G,ext}(T_{ext} - T_{1_e}) + A_{x=0} I_o \qquad (17)$$

where, $h_{G,ext}$ represents the external global film coefficient and corresponds to the sum of the convective and radiation coefficients $h_{G,ext} = h_{C,ext} + h_{R,ext}$,

$$h_{R,ext} = \varepsilon\sigma(T_{1_e}^2 + T_{ext}^2)(T_{1_e} + T_{ext}) \qquad (17a)$$

with ε as the emissivity of glass, and σ = 5,67 x 10^{-8} the Stefan-Boltzman constant, A is the absorptivity and I_o is the incident solar radiation.

b) At x = x_1 the boundary condition depends on the state of the PCM. There will be three possible boundary conditions. From the energy balance at the glass-PCM interface,

(b1) PCM is solid, when it is below the phase change temperature (T_{pc})

$$-k_1 \left.\frac{\partial T_1}{\partial x}\right|_{x=x1} + A_{x=x1} I_o = -k_S \left.\frac{\partial T_S}{\partial x}\right|_{x=x1} \qquad (18)$$

(b2) PCM near the internal face of the external glass sheet where the first liquid film of the PCM is formed

$$-k_1 \left.\frac{\partial T_1}{\partial x}\right|_{x=x1} + A_{x=x1} I_o = \rho H \frac{dS(t)}{dt} - k_S \left.\frac{\partial T_S}{\partial x}\right|_{x=x1} \qquad (19)$$

(b3) PCM near external glass face is in the liquid phase

$$- k_1 \frac{\partial T_1}{\partial x}\Big|_{x=x1} + A_{x=x1}\, I_o = -k_L \frac{\partial T_L}{\partial x}\Big|_{x=x1} \qquad (20)$$

c) At $x=x_1 + S(t)$, it corresponds to the liquid-solid interface position in the region where the phase change occurs due to the thermal gain. Performing a thermal balance at the phase change front we have

$$-k_L \frac{\partial T_L}{\partial x} + k_S \frac{\partial T_S}{\partial x} + A_{x=x1+S(t)} I_o = \rho H \frac{dS(t)}{dt} ,$$
$$T_L = T_S = T_{PC} \qquad (21)$$

d) In the same manner as at $x = x_1$, the boundary condition at $x = x_2$ will depend on the state of the phase change material near the internal glass surface, giving rise to three possible boundary conditions

d1) $x_1 < S(t) < x_2$; solid phase still exists

$$k_S \frac{\partial T_S}{\partial x}\Big|_{x=x_2} = k_3 \frac{\partial T_3}{\partial x}\Big|_{x=x_2} \qquad (22)$$

d2) last solid layer

$$- k_L \frac{\partial T_L}{\partial x}\Big|_{x=x2} + A_{x=x2} I_o = \rho H \frac{dS(t)}{dt} - k_3 \frac{\partial T_3}{\partial x}\Big|_{x=x2} ,$$
$$T_L = T_3 = T_{PC} \qquad (23)$$

(d3) PCM material totally in the liquid phase

$$- k_L \frac{\partial T_L}{\partial x}\Big|_{x=x2} + A_{x=x2} = -k_3 \frac{\partial T_3}{\partial x}\Big|_{x=x2} \qquad (24)$$

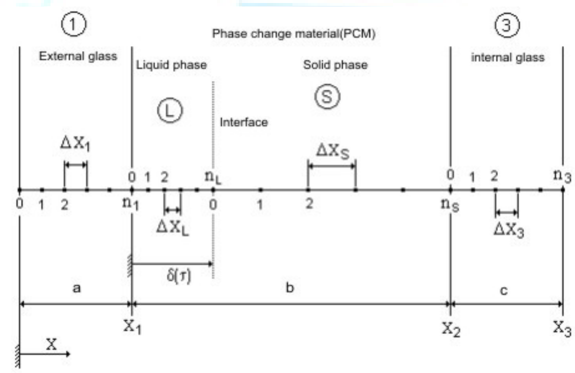
e) At $x = x_3$

$$- k_3 \frac{\partial T_3}{\partial t}\Big|_{x=x_3} = h_{G,int}\left(T_3 - T_{int}\right) \qquad (25)$$

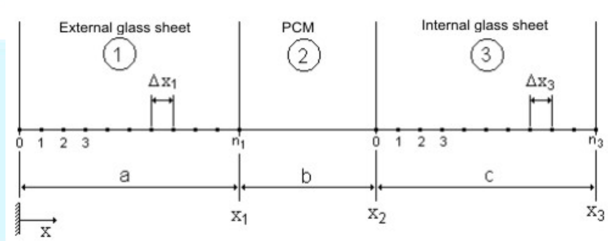
where, $h_{G,int} = h_{C,int} + h_{R,int}$ represents the internal global film coefficient and corresponds to the sum of the convective and radiation coefficients,

$$h_{R,int} = \varepsilon\sigma(T_{3_i}^2 + T_{int}^2)(T_{3_i} + T_{int}) \qquad (25a)$$

The above equations and the associated boundary conditions were put in dimensionless form to facilitate the numerical calculations. The non-dimensional equations and the boundary conditions were treated using an explicit finite difference scheme. In the PCM region a moving grid procedure based on Murray and Landis work [26] was used. Each phase was divided into 10 increments in the liquid and solid regions, respectively. Each glass sheet was also divided into 10 equally spaced increments along the glass thickness. Details of the computational grids are shown in Fig. 19, where Fig. 19a shows the moving grid scheme used in the PCM layer while Fig. 19b shows the fixed grid scheme used for the internal and external glass of the panel. Additional information and details on the development of the numerical simulation can be found in [6].



(a)



(b)

Fig. 19 Computational grids for internal and external glass and the PCM layer.

It is worth mentioning that the incident solar radiation was simulated based upon Liu and Jordan model [27] and the local meteorological and geographical data of the city of Campinas, Brazil. This model includes direct, diffuse and reflected radiation. The hourly variation of the outdoor air temperature is calculated based upon the procedure recommended in ASHRAE Handbook of Fundamentals [28].

4. Results and discussion

The numerical simulations were realized for the same configurations for which the optical characterization was realized. The temperature distributions across the window panel, evolution of the internal and external surfaces of the panel and finally the heat gain of the internal ambient were obtained from the numerical predictions. The heat gain calculated here is the sum of two parcels; the first is due to transmitted solar radiation through the glass sheets and absorbed by the internal ambient, while the second parcel is due the temperature difference between the internal and external ambient. These two parcels are calculated per unit area of the glass sheet.

Fig. 20 shows the total heat gain, solar heat gain and the heat gain due to temperature difference between the internal and external ambient temperatures for the case of a window of clear glass of 8 mm thickness. As can be observed, the dominant contribution to the total heat gain is the incident solar radiation.

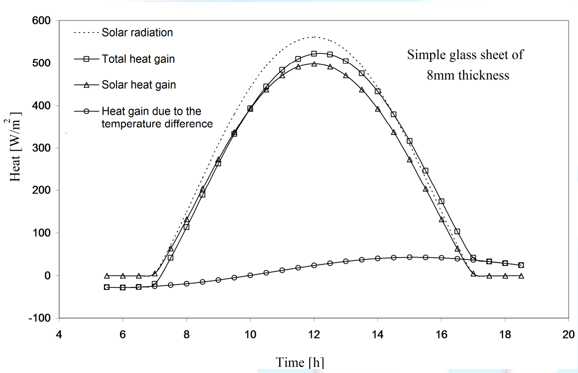


Fig. 20 Heat gain for a simple glass window of 8 mm thickness.

Simulations were realized for simple glass windows of 3, 4, 5, 6, and 8 mm thickness. Fig. 21 shows a typical simulation result and the other curves were omitted for brevity. As can be seen not only the temperature difference between the internal and external surfaces is marginally small but also the heat gain and the incident radiation are nearly equal which means that the simple glass window is ineffective and allows nearly all solar radiation to penetrate into the internal ambient.

Fig. 22 shows a summary of the thickness effect in the case of simple glass windows indicating that thickness increase reduces transmitted heat only by a small amount.

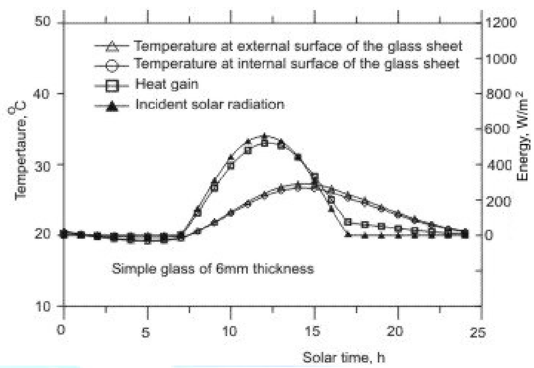


Fig. 21 Predicted solar heat gain, and temperatures of the internal and external surfaces of simple glass panel of 6 mm thickness.

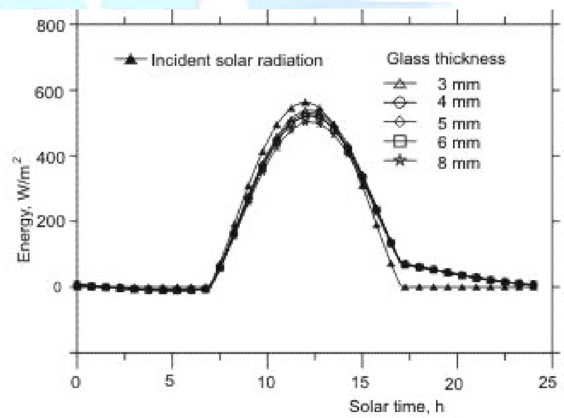


Fig. 22 Variation of the solar heat gain with glass thickness for simple glass panels.

To investigate the effect of spacing between the glass sheets of double panel on the transmitted heat gain and indoor temperature, simulations were realized on configurations of 6mm thickness with spacing of 3, 6, and 8 mm filled with air. Fig. 23 shows a typical result for spacing of 6mm. The solar heat gain is found to follow the same tendency of thee incident solar radiation with nearly a coincident peak around mid day. The peak of indoor temperature occurs is displaced way after the peaks of solar radiation and solar heat gain due to thermal inertia effects. A comparison between the double glass panel shows better thermal performance and less heat gain in comparison with the incident solar radiation. This reduction can be attributed to the air layer as can be verified by the noticeable temperature difference between the internal and external glass sheets.

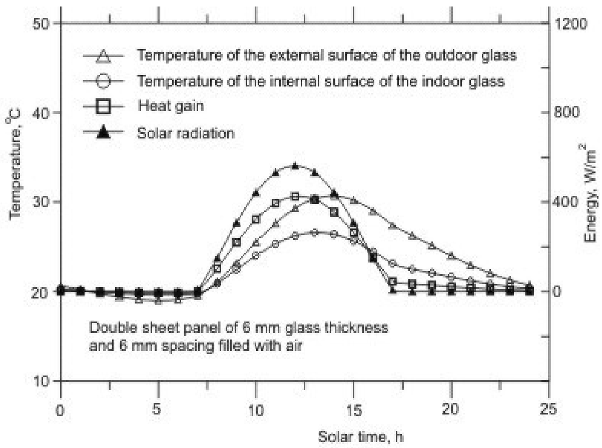


Fig. 23 Predicted solar heat gain, and temperatures for the double glass panel of 6 mm thickness and 6 mm spacing filled with air.

Fig. 24 shows summary of the results of the effect of varying the spacing filled with air. One can observe that increasing the spacing has a small effect on the solar heat gain. The presence of air space reduces the heat gain in comparison with the case of simple glass sheet of Fig. 21.

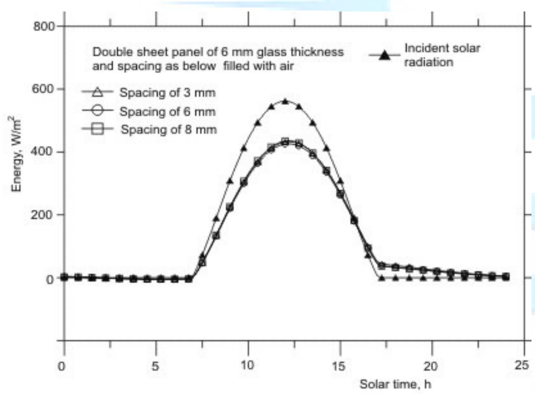


Fig. 24 Variation of the solar heat gain with sheet spacing for double glass panels of 6 mm glass thickness filled with air.

To investigate the effect of glass thickness in double glass configuration the spacing between the glass sheets was fixed at 3mm. The glass thickness was varied from 3 to 8mm. Fig 25 shows a result for double glass configuration of thickness of 4mm thickness indicating a reduction of the heat gain and noticeable temperature difference between the internal and external glass sheets. Fig. 26 shows a summary of the results of the effect of glass thickness for the double glass configuration indicating a reasonable reduction in the heat gain in comparison to the incident solar radiation.

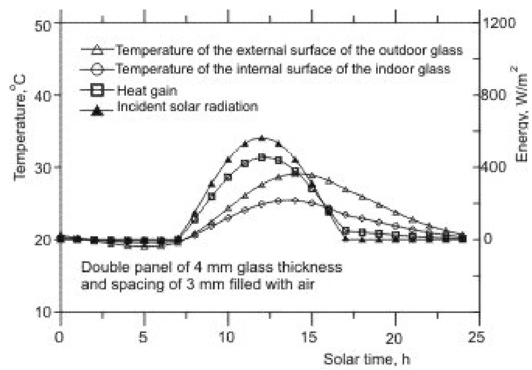


Fig. 25 Predicted solar heat gain, and temperatures for the double glass panel of 4 mm thickness and 3 mm spacing filled with air.

To investigate the effect of inserting a layer of PCM in the spacing between glass sheets the same glass configurations filled with air were simulated with PCM to enable comparison of results. Representative result is shown in Fig. 27 from which one can observe that increasing the PCM thickness reduces the solar heat gain much more than in the case of air filled spacing or simple glass window.

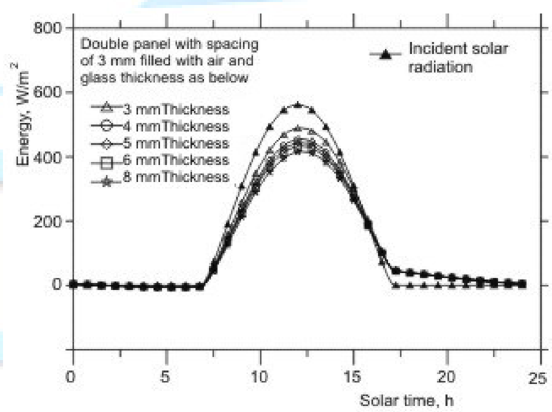


Fig. 26 Variation of the solar heat gain with glass thickness for double glass panels of 3 mm spacing filled with air.

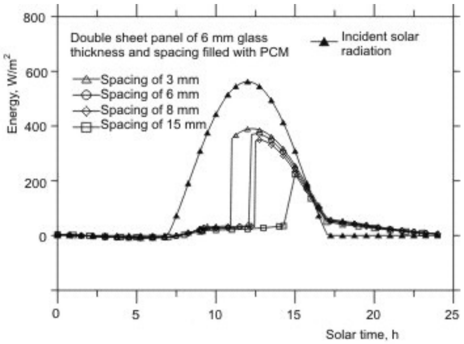


Fig. 27 Variation of the solar heat gain with the width of spacing filled of PCM for double glass panels of 6 mm glass thickness.

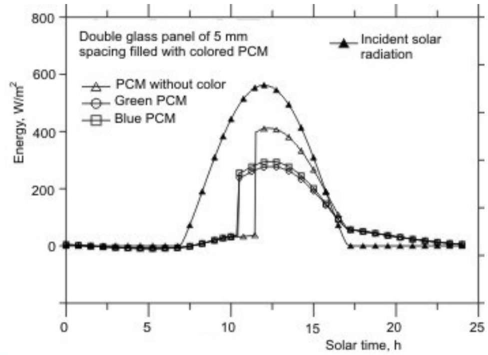


Fig 28 Variation of the transmitted energy with the color of PCM.

The dimension of the PCM layer is critical for the control of the indoor temperature. As long as the PCM is not fully melted, the temperature of the indoor glass surface in contact with the PCM will also be constant. This situation is maintained until the full melting of PCM after which any available solar will cause increasing the indoor temperature. This means greater thickness is needed to guarantee full melting of PCM until sunset. This in a way is a critical issue that must be addressed correctly since thick PCM layer increases weight of the window system, reduces visibility and natural illumination beside the necessity of mechanically reinforcing the glass panel.

The effect of color of the PCM on the transmitted energy and solar heat gain is also investigated mainly due to the fact that when PCM is in the solid phase it is opaque and adding a color makes the indoor ambient more pleasant. Green and blue colored PCM were used as filling material for double glass window of 4mm glass thickness and spacing of 5mm. The results are shown in Fig. 28 where the base line case of PCM without any color is included to help comparison. The curves corresponding to the cases of green and blue PCM fillings show a lot less energy transmitted than the case of uncolored PCM. On the other hand they melt before the uncolored PCM due to the high absorptivity coefficient of the colored PCM as shown in the optical tests realized on PCM. This behavior does not necessarily deteriorate their thermal behavior taking into consideration the fact that the transmissivity of the colored PCM is less than that of the uncolored PCM and hence compensate the undesired effect due to the high absorptivity of the colored PCM resulting in higher thermal performance of the colored PCM.

5. Conclusions

The present study reveals that the inclusion of PCM in the spacing between glass sheets in double glass windows helps reducing transmitted solar energy to the indoor ambient and that colored PCM (green and blue) can reduce more this transmitted energy. The simulations show that the proposed model represent well the double glass window and predicted its thermal behavior. The beneficial effect of the PCM is implicitly due to its thickness, that is, the PCM thickness must be enough to satisfy the condition of total melting at about sunset and total solidification until sunrise. Increasing the PCM layer thickness can reduce the window visibility and increase its weight. Colored PCM is found to enhance the performance of the double glass window. This investigation reveals that the PCM double glass window can reduce the cooling load while maintaining constant indoor temperature and relatively good visibility.

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