MODELS FOR THERMALLY EFFICIENT DOUBLE GLASS WINDOWS

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Abstract
Glass windows are essential elements in residential and commercial buildings for esthetic and natural illumination reasons. They are the transparent barriers between the external and internal ambient allowing heat exchange between them, thermal losses and undesirable heat gains. In recent years many experimental, numerical and theoretical investigations were devoted to study and develop efficient glass windows, improve their thermal performance to reduce the thermal gains and losses while maintain the esthetics and natural illumination aspects. The present study reports the results of three models developed for double glass windows. The models are for forced air flow double glass window, double glass window filled with PCM which and double glass window filled with stagnant air. Some of the results of these models are presented to show their respective contributions to the solar heat gain and the solar shade factor.

Keywords: Solar heat gain; solar shade factor; low energy buildings; double glass windows; PCM windows; Air filled windows.

1. Introduction

From the thermal view point glass windows are the weakest elements in a building which separate the external and the internal ambient. In cold climates windows are usually responsible for about 10-25% of the thermal losses in heated ambientes. In hot climates the excess of solar radiation penetrating through windows increases the expenditure with air conditioning. An efficiente way to reduce the excessive heat penetration in hot climates is to use passive mechanisms which reduce the penetration of direct solar radiation. Curtains and blinds are commonly used as passive system to control and reduce the incidence of direct solar radiation. In cold climates there is a necessity to enhance the solar radiation through the glass systems. Windows of simple glass sheet are are weak barriers against incident solar radiation. The clear glass has transmission index of about 90% allowing the penetration of nearly all the solar radiation which is transformed to heat when absorved by internal ambient. Also the common glass sheet has a low thermal resistence which allows more heat conduction between the internal and external ambientes.

The development of new materials and advanced manufacturing technologies associated with public policies to reduce energy consumption made possible the evolution of windows technologies and the production of thermally more efficient windows. Windows having selective solar radiation characteristics are examples of thermally efficient windows. The selective properties due to deposited films on glass sheets allow reducing the transmittance and absorptance of the window and increasing reflectance. These films can be designed to absorb or reflect according to the wavelength of the incident radiation. High performance is also achieved by using evacuated glass panels where heat transfer by conduction and convection is greatly reduced. The use of absorbing gases filling the gap between glass sheets appears to be an alternative solution for thermally insulated glass windows. Available glazing systems can provide very good solutions for cold climate conditions, and fairly effective ones for warm climates. However, there is still no window system on the market that can offer the flexibility required, providing a comfortable visual environment and an efficient energy response in climates where heating is required in winter and cooling is required in summer.

To cope with the sustainability and conservation needs, window technology is currently under rapid evolution. A number of innovations in recent years have given window glazing a revised identity as well as a wide range of design options. Some glass window concepts were investigated using alternative filling materials such as silica aerogel by (Einarsrud et al., 1993), phase change materials as in (Ismail and Henríquez, 2002).

Etzion and Erell (2000) escribed a novel ventilated reversible glazing system to control the transmission of radiant energy through windows. Their glazing system was designed to overcome glare and radiation damage to interior furnishings, yet causes no reduction in the energy efficiency of the glazed opening compared with a conventional window.

The use of gases with strong infrared radiation absorption characteristics was investigated and some simplified models for spectral radiation modeling was formulated by (Ismail and Salinas, 2006).

Gosselin and Qingyan (2008) developed a computational method for calculating heat transfer and airflow through a dual-airflow window, which has great potential for conserving energy and improving indoor air quality in residential buildings. Experimental tests on a full-scale dual-airflow window system were used to validate the computer method showing good agreement.

Chow et al. (2010) developed a solar window for cooling-demand climate. Their paper describes an innovative concept of water-flow window and discusses the potential areas of application. The results indicate that this new design is able to support hot water supply system, reduce air-conditioning load and enhance thermal and visual comfort.

Goia et al. (2012) reported a numerical investigation of the thermo-physical behavior and energy performance assessment of PCM glazing system configurations including various triple glazing configurations.

Alawadhi (2012) reported the results of a study on using phase change materials in window shutter to reduce the solar heat gain. The window shutters are typically made of foam filled aluminum rolling shutter slat. The result indicates that the heat gain through windows can be reduced as high as 23.29%.

Goia et al. (2013) investigated the improvement of thermal comfort conditions by means of PCM glazing systems. In their work, a prototype of a simple PCM glazing system is proposed and its behavior is compared with that of a conventional reference double glazed unit.

Chow and Chunying (2013) presented a liquid-filled solar glazing design for buoyant water-flow. A water-flow window was constructed at the front wall of an environmentally controlled test cell to monitor its performance under full-scale real-building-like condition. A comparative study was also carried out with the use of different glazing types.

The present paper presents three models for thermally efficient windows. The investigated models are: double glass window under forced flow conditions, double glass window with air in the gap between glass sheets and double glass window with PCM in the gap between glass sheets. The thermal characteristics of the three types of windows such as the shading coefficient and the solar heat gain are evaluated.

2. The proposed models

2.1 Double glass window with forced airflow

The problem of double glass window with forced airflow can be simplified as two parallel glass sheets of height L, width w and a gap b, and open at the upper and lower ends as in Fig. 1. Circulating air forced between the glass sheets cools the glass sheets as it passes in the channel. The external glass sheet receives the incident solar radiation, part of which is absorbed and the rest hits the internal glass where some of it is absorbed and the rest is delivered to the internal ambient. The surfaces of the glass sheets in contact with the air in the channel exchange heat by convection and by radiation. Part of the solar radiation which crosses the external glass is absorbed by the internal glass, increases its temperature and causing exchange of heat by convection and radiation. Fig. 1 shows the mechanisms of heat transfer for a ventilated glass window.

The governing equations of the problem are deduced by performing energy balances over the control volumes in the fluid and glass sheet. The glass-fluid system is subdivided into n layers in the flow direction forming a grid of $3x\ n$ control volumes (3 control volumes in each layer).

Considering an arbitrary layer i, one can write the energy balance for each control volume in the layer formed by the external glass, fluid and internal glass as shown in Fig. 2.

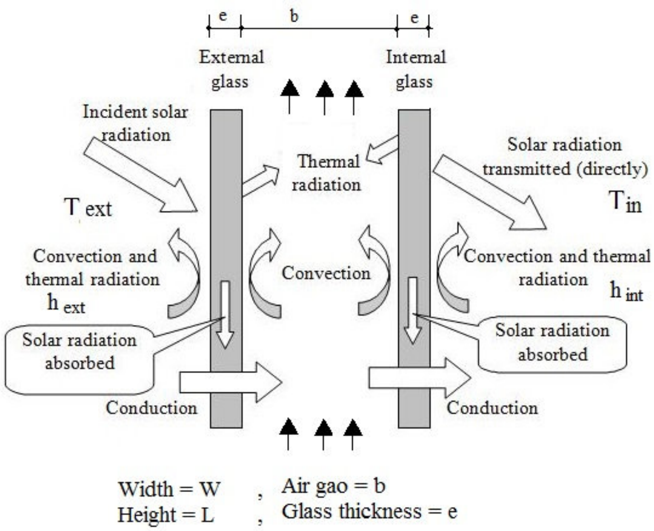

Fig. 1 Mechanisms of heat transfer for a ventilated glass window.

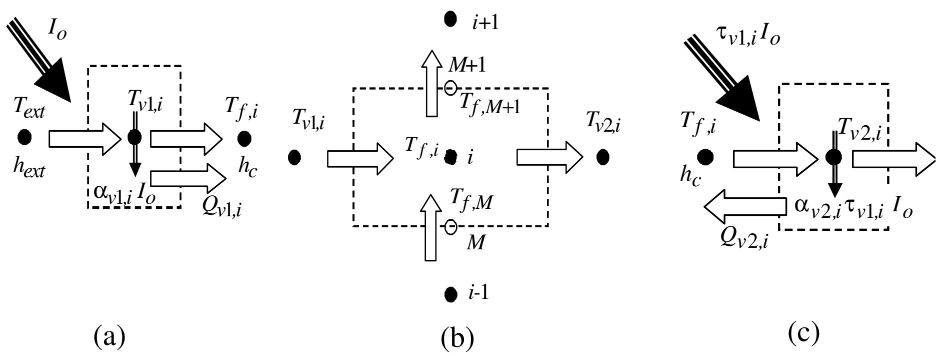

Fig. 2 Elementary control volume in a) external glass (b) fluid and (c) internal glass

For the control volume i in the fluid, external glass and internal glass one can write

$$(\rho c V)_f \frac{\partial T_{f,i}}{\partial t} = \dot{m}c\left(T_{f,M} - T_{f,M+1}\right) + h_c A\left(T_{eg,i} - T_{f,i}\right) + h_c A\left(T_{ig,i} - T_{f,i}\right) \tag{1}$$

$$(\rho c V)_{eg} \frac{\partial T_{eg,i}}{\partial t} = h_{ext} A\left(T_{ext} - T_{eg,i}\right) + h_c A\left(T_{f,i} - T_{eg,i}\right) + \sigma\varepsilon_{eg} A\left(T_{ext}^4 - T_{eg,i}^4\right) + \alpha_{\mathrm{eg}} I_o + Q_{eg,i} \tag{2}$$

$$(\rho c V)_{ig,i} \frac{\partial T_{ig}}{\partial t} = h_{\mathrm{int}} A\left(T_{\mathrm{int}} - T_{ig,i}\right) + h_c A\left(T_{f,i} - T_{ig,i}\right) + \sigma\varepsilon_{ig} A\left(T_{\mathrm{int}}^4 - T_{ig,i}^4\right) + \alpha_{\mathrm{ig}}\tau_{eg} I_o + Q_{ig,i} \tag{3}$$

In Eq. (1), the temperature at the faces of the control volume and its center appear in the equation. Considering that the control volume is small, one can consider that the temperature at the center is the mean temperature of the faces,

$$\mathrm{T_{f,i}} = \frac{\mathrm{T_{f,M+1}} + \mathrm{T_{f,M}}}{2} \tag{4}$$

which when substituted in Eq. (13) one obtains

$$\frac{(\rho c V)_f}{2}\frac{\partial\left(T_{f,M+1}+T_{f,M}\right)}{\partial t}=\dot{m}c\left(T_{f,M}-T_{f,M+1}\right)+h_c A\left(T_{eg,i}-\left(\frac{T_{f,M+1}+T_{f,M}}{2}\right)\right)+ h_c A\left(T_{ig,i}-\left(\frac{T_{f,M+1}+T_{f,M}}{2}\right)\right) \quad (5)$$

Eqs. (2), (3) and (5) are applied for each control volume from $i=1$ to $i=n$, and can be solved numerically by finite difference. Initially the temperature field in the channel and in the glass sheets is known and considered uniform. From the boundary condition at entry to the channel, the temperature and fluid mass flow are known at this point, permitting calculating the exit temperature from the first control volume in the fluid. Knowing this temperature and the temperature at entry, an average temperature can be obtained in the first fluid control volume and hence the temperature of the first control volume of the internal and external glass. This procedure is repeated for each control volume by marching in the vertical direction until the last control volume in the channel and is repeated for each time interval until the simulation time is terminated.

The Solar Heat Gain Coefficient and the Shading Coefficient are calculated using the procedure presented earlier and the total heat gain can be calculated from Eq.6.

$$q_{total}=\frac{1}{n\Delta x}\sum_{i=1}^{n}h_{int}\Delta x\left(T_{ig,i}-T_{int}\right)+\sigma\varepsilon_i\Delta x\left(T_{ig,i}^4-T_{int}^4\right)+\tau_{ig}\tau_{eg}I_o\Delta x \quad (6)$$

where the subscript i refers to a given control volume of the internal glass sheet. The sum of energy balances over each element allows calculating the total heat gain (q_{total}).

The predictions from this model are presented in the discussion section.

2.2 Double glass window with gap filled with air

A model for double glass window with gap filled with air and subject to solar radiation of intensity I_o is shown in Fig. 3. Considering that the differential heat conduction is valid for each layer of the window system, one can write

$$\frac{\partial T}{\partial t}=\alpha\frac{\partial^2 T}{\partial x^2}-\frac{1}{\rho C}\frac{\partial I}{\partial x} \quad (7)$$

The problem can be analyzed in parts starting by the external glass sheet,

$$\frac{\partial T_1}{\partial t}=\alpha_1\frac{\partial^2 T_1}{\partial x^2}-\frac{1}{\rho_1 C_1}\frac{\partial I}{\partial x} \quad (8)$$

Subject to boundary and initial conditions as

i) at x = 0, energy balance at the surface gives:

$$-k_1\frac{\partial T_1}{\partial x}=A_{x=0}I_0-h_{C,ext}(T_{1e}-T_{ext})-\varepsilon\sigma\left(T_{1e}^4-T_{ext}^4\right)$$

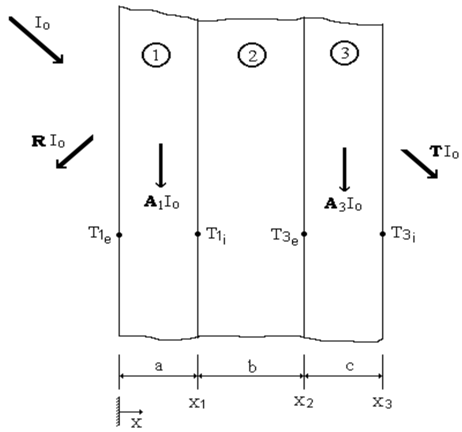

Fig. 3 Scheme of a double glass window filled with air.

Where the first part on the right side is the absorbed solar radiation; the second part is the heat exchanged by convection between the external surface and the external ambient while the third part represents the heat flux exchanged by radiation with the external ambient.

$$h_{G,ext} = h_{C,ext} + \varepsilon\sigma\left(T_{1e}^2 + T_{ext}^2\right)\left(T_{1_e} + T_{ext}\right) \qquad (9)$$

$$-k_1 \frac{\partial T_1}{\partial x} = A_{x=0} I_0 - h_{G,ext}\left(T_{1_e} - T_{ext)}\right) \qquad (10)$$

ii) at $x = x_1$

$$-k_1 \left.\frac{\partial T_1}{\partial x}\right|_{x=x_1} = C_1\left(T_{1_i} - T_{3_e}\right) \qquad (11)$$

where

$$C_1 = h_{C,gap} + h_{R,gap} \qquad (12)$$

At region 2 there is heat transfer by convection, conduction and radiation along with short wave length radiation which pass through the first glass.

To determine the coefficient $h_{C,gap}$ consider natural convection in the air space between the two vertical sheets, Holman (1983)

$$h = \frac{k_f}{b} Nu \qquad (13)$$

Where k_f is the thermal conductivity of the confined air, b is the space between the glass sheets and Nu is the Nusselt number in the confined space which can be determined from the empirical correlation for vertical windows given by Arasteh[1989]

$$Nu = [1 + (0,0303 Ra^{0,402})^{11}]^{0,091} \qquad \text{Para } Ra < 2\times10^5 \qquad (14)$$

Where Ra is the Rayleigh number is the product of the Grashoff number Gr and the Prandtl number Pr, where Gr is defined as

$$Gr = \frac{g\beta\rho^2 b^3 \Delta T}{\mu^2} \qquad (15)$$

Where g is the gravitional acceleration; β is the coefficient of thermal expansion; ρ is the density of the fluid; μ is the dynamic viscosity and ΔT is the temperature difference.

When Grashof number is very small (Gr smaller than 2000, the convection currents are also small and heat transfer occur in this case by conduction through the air layer, Kreith[1977]. Performing some calculations (ommited here for brevity) it is possible to consider for the gap range 0 to 15 mm that the convective effects in region 2 can be neglected.

To determine h_R one must solve the radiation heat transfer problem between two parallel infinite plates of areas A_1 and A_3 where the form factor F_{13} is unity, by using Duffie [1980].

$$Q_1 = \frac{\sigma(T_{1_i}^4 - T_{3_e}^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{13}} + \frac{1-\varepsilon_3}{\varepsilon_3 A_3}} \tag{16}$$

In this way the equation is reduced to

$$\frac{Q_1}{A} = \frac{\sigma(T_{1_i}^4 - T_{3_e}^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_3} - 1}$$

which can be written as

$$\frac{Q_1}{A} = \frac{\sigma E(T_{1_i}^4 - T_{3_e}^4)}{(T_{1_i} - T_{3_e})}(T_{1_i} - T_{3_e})$$

and

$$h_R = \sigma E \frac{(T_{1_i}^4 - T_{3_e}^4)}{(T_{1_i} - T_{3_e})} \tag{17}$$

$$E = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_3} - 1} \tag{18}$$

ε_1 and ε_3 are the emissivities of the external glass and the internal glass, and can be assumed as 0.9 and 0.95, respectively.

Performing an analysis similar to that of the internal glass one can write

$$\frac{\partial T_3}{\partial t} = \alpha_3 \frac{\partial^2 T_3}{\partial x^2} - \frac{1}{\rho_3 C_3}\frac{\partial I}{\partial x} \tag{19}$$

With the boundary conditions

i) at $x = x_2$

$$-k_3 \left.\frac{\partial T_3}{\partial x}\right|_{x=x_2} = A_{x=x_2} I_0 + C_1\left(T_{1i} - T_{3e}\right) \tag{20}$$

Where $C_1 = h_{C,gap} + h_{R,gap}$

ii) at $x = x_3$

$$-k_3 \left.\frac{\partial T_3}{\partial x}\right|_{x=x_3} = h_{G,int}\left(T_{3i} - T_{int}\right) \tag{21}$$

Where $h_{G,int}$ is defined as the sum of the convective and radiative coefficients and can be written as

$$h_{G,int} = h_{C,int} + \varepsilon\sigma\left(T_{3i}^2 + T_{int}^2\right)\left(T_{3i} + T_{int}\right) \tag{22}$$

The numerical predictions from this model are presented in the discussion section.

2.3 Double glass window with PCM

The concept of double glass window with PCM is relatively simple and effective. It is formed of double glass window separated by a gap filled with a PCM of certain fusion temperature as shown in Fig.4. In operation 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 region (initially in the solid phase), which absorbs part of the energy received and reflects the rest. 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 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 project will ensure that the external temperature will start to decline before total fusion of the enclosed 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 panel

The differential equation for each region is

$$\frac{\partial T_i}{\partial t} = \alpha_i \frac{\partial^2 T_i}{\partial x^2} - \frac{1}{\rho_i C_i}\frac{\partial I}{\partial x} \tag{23}$$

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

$$-k_1 \left.\frac{\partial T_1}{\partial x}\right|_{x=0} = h_{G,ext}(T_{ext} - T_{1_e}) + A_{x=0} I_o \tag{24}$$

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

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

with ε as the emissivity of glass, and $\sigma = 5,67 \times 10^{-8}$ the Stefan-Boltzman constant.

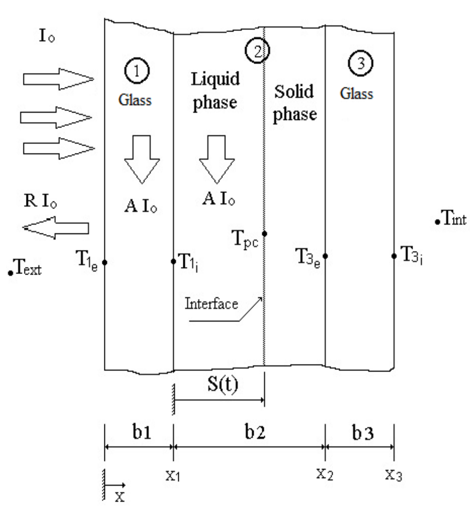

Fig. 4 Scheme of the double glass window with gap filled with PCM.

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})

$$-k_1 \frac{\partial T_1}{\partial x}\bigg|_{x=x1} + A_{x=x1}\, I_o = -k_S \frac{\partial T_S}{\partial x}\bigg|_{x=x1} \qquad (25)$$

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

$$-k_1 \frac{\partial T_1}{\partial x}\bigg|_{x=x1} + A_{x=x1}\, I_o = \rho H \frac{dS(t)}{dt} - k_S \frac{\partial T_S}{\partial x}\bigg|_{x=x1} \qquad (26)$$

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

$$-k_1 \frac{\partial T_1}{\partial x}\bigg|_{x=x1} + A_{x=x1}\, I_o = -k_L \frac{\partial T_L}{\partial x}\bigg|_{x=x1} \qquad (27)$$

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

$$-k_L \frac{\partial T_L}{\partial x} + k_S \frac{\partial T_S}{\partial x} + A_{x=x1+S(t)} I_o = \rho H \frac{dS(t)}{dt} \quad , \quad T_L = T_S = T_{PC} \qquad (28)$$

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

$$k_S \frac{\partial T_S}{\partial x}\bigg|_{x=x_2} = k_3 \frac{\partial T_3}{\partial x}\bigg|_{x=x_2} \qquad (29)$$

(d2) last solid layer

$$-k_L \frac{\partial T_L}{\partial x}\bigg|_{x=x2} + A_{x=x2} I_o = \rho H \frac{dS(t)}{dt} - k_3 \frac{\partial T_3}{\partial x}\bigg|_{x=x2} \quad , \qquad T_L = T_3 = T_{PC} \qquad (30)$$

(d3) PCM material totally in the liquid phase

$$-k_L \frac{\partial T_L}{\partial x}\bigg|_{x=x2} + A_{x=x2} = -k_3 \frac{\partial T_3}{\partial x}\bigg|_{x=x2} \qquad (31)$$

e) At $x = x_3$

$$-k_3 \frac{\partial T_3}{\partial t}\bigg|_{x=x_3} = h_{G,int}\left(T_3 - T_{int}\right) \qquad (32)$$

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

The equations together with the boundary conditions were solved using an explicit finite difference scheme. In the PCM region a moving grid procedure is used. Each phase is divided into 10 increments □X_L and □X_S in the liquid and solid regions respectively. Each glass sheet was also divided into 10 equally spaced increments along the glass thickness.

It is known that the coefficient of solar heat gain of a given system is defined as a fraction of the incident solar radiation penetrating the internal ambient and is composed of two components;

1. solar radiation which penetrates directly and is absorbed by the internal ambient;
2. solar radiation absorbed by the window system and directed to the interior via the heat transfer mechanisms.

The first component is determined by calculations involving the optical properties of the window system and the solar radiation data. Windows for residential applications are generally designed to have a high transmittance in the visible range and consequently present a high transmittance for the solar radiation. The second component can be determined by using the solar optical properties of the window system as well as the heat transfer mechanisms. Consequently, for a simple glass system one can write

$$F = \tau + \alpha \frac{U}{h_{ext}} \tag{33}$$

where τ is the transmittance of the window system corresponding to the fraction of the incident solar radiation directly transmitted through the window system, α is the absortance coefficient of the window system and U is the thermal conductance. $\alpha U/h_{ext}$ is the fraction of the radiation absorbed. The effects of the temperature difference between the external and the internal ambients as well as the internal and external air velocities are included in U/h_{ext} .

In the case of double glass window systems one can write the coefficient of heat gain as

$$F = \tau_{Global} + \alpha_1 \frac{U}{h_{ext}} + \alpha_2 \left[\frac{U}{h_{ext}} + \frac{U}{h_{gap}} \right] \tag{34}$$

where α_1 and α_2 are the absortance coefficients of the two glass sheets respectively and h_{gap} is the films coefficient of the confined air in the gap.
The numerical predictions from this model are presented in the discussion section.

3. Discussion

In the simulations realized for variable incident solar radiation and variable external ambient temperature, a north facing glass window localized at the city of Campinas-SP, Brazil, latitude of $22^o 53'$ South and $47^o 5'$ East is adopted in the simulations.

Fig. 5 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. 6 shows comparative results for clear glass of thickness 3, 6 and 8 mm indicating that the effect of the glass thickness of clear glass is relatively small. The thermal model for the simple glass window is omitted for the sake of brevity.

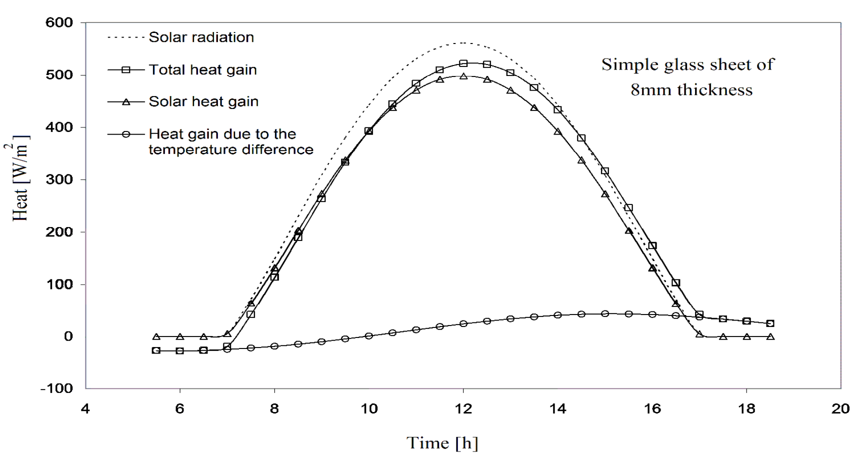

Fig. 5 Heat gain for a simple glass window of 8 mm thickness.

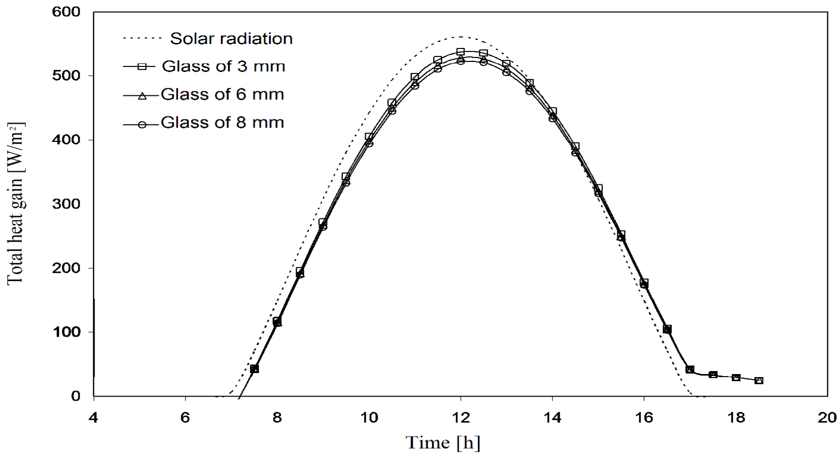

Fig. 6 Comparison of the total heat gain for glass windows of three different thicknesses.

Fig. 7 shows the effect of air mass flow rate on the temperature of the internal glass sheet at its mid height position. As can be seen the increase of the mass flow rate reduces the internal glass temperature and the total heat gain in comparison with the simple glass window as in Fig. 8.

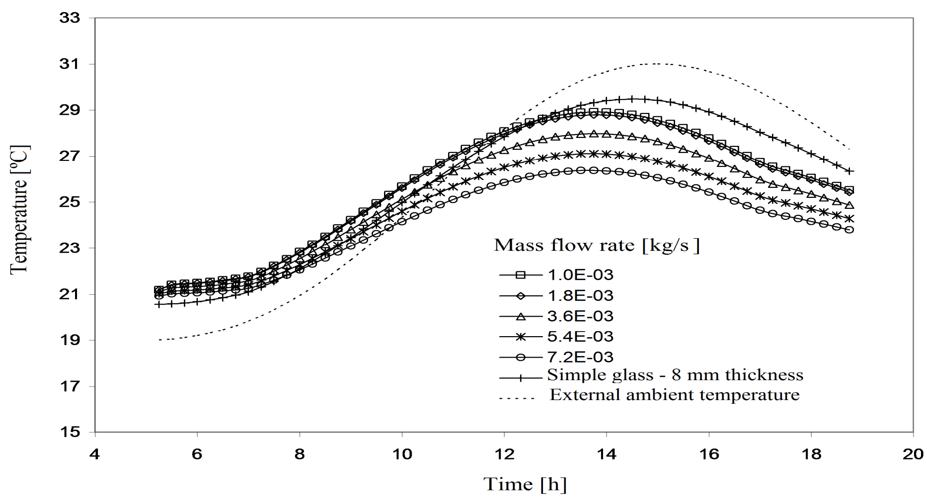

Fig. 7 Effect of the air mass flow rate on the internal glass surface temperature.

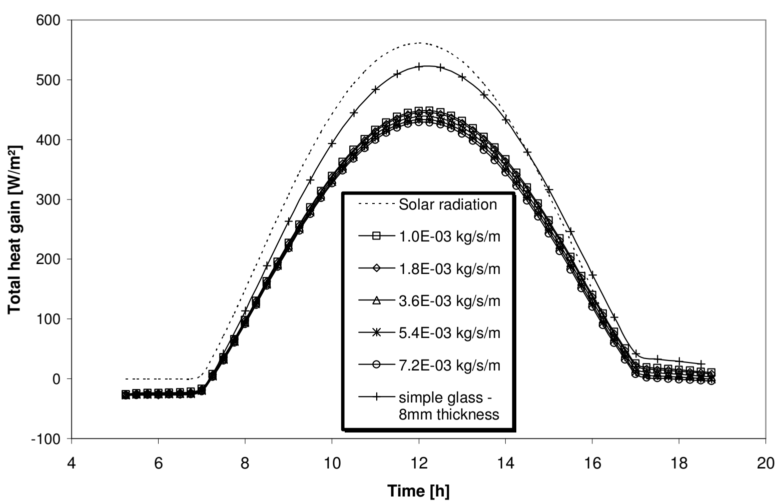

Fig. 8 Variation of the total heat gain with time.

Fig. 9 shows the Total Heat Gain, Solar Heat Gain and the Heat Gain due to the difference between the internal and external ambient temperatures showing that the incident solar radiation has a dominant contribution to the Total Heat Gain.

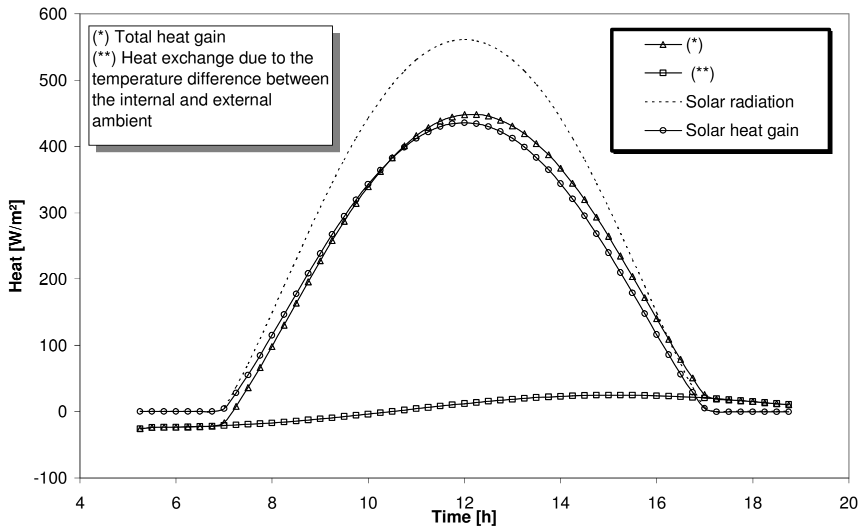

Fig. 9 Comparison between the heat gain with and without including the solar radiation exchange.

If the instantaneous Solar Heat Gain Coefficient (F) and Shading Coefficient (SC), are integrated over the incidence period of solar radiation, one can obtain the average values of these coefficients. Table 1 shows the calculated average values of Solar Heat Gain Coefficient and Shading Coefficient for different values of mass flow rate. As can be seen both the values of SC and F decrease with the increase of the mass flow rate and are well below the case of a simple glass window.

Table 1 Values of F and SC for forced convection ventilated window

Ventilated window		Solar heat gain coefficient (F)	Shading coefficient SC
Mass flow rate $[\mathrm{kg/s/m}]$	1.0×10^{-3}	0.779	0.855
	1.8×10^{-3}	0.776	0.852
	3.6×10^{-3}	0.769	0.844
	5.4×10^{-3}	0.765	0.840
	7.2×10^{-3}	0.762	0.836
Simple glass windows 8 mm		0.89	0.978

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Fig. 10 shows the variation of the external and internal temperatures of the glass and the heat gain against solar time in hours for double glass window filled with air.

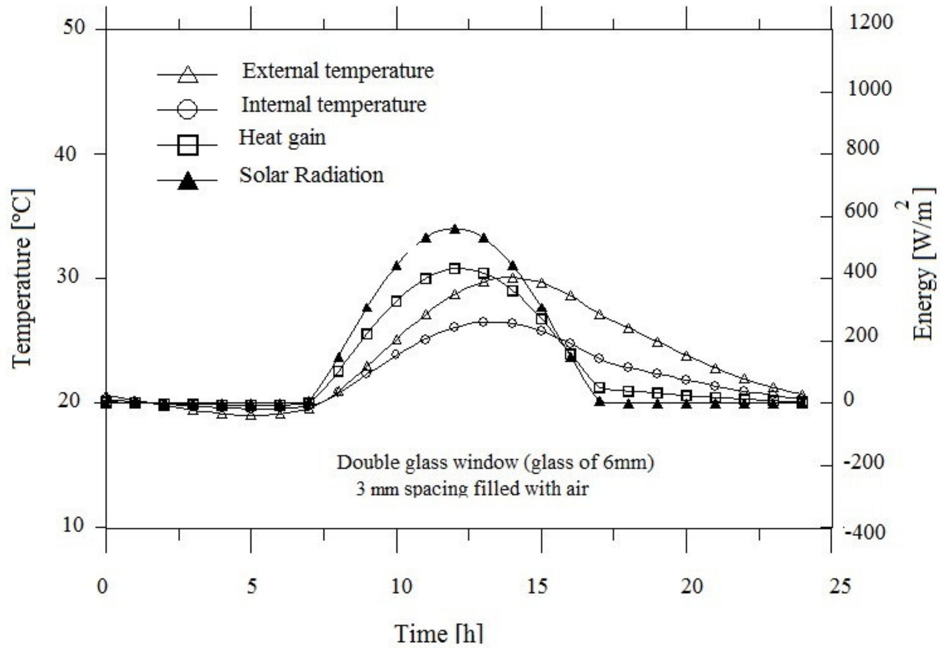

Fig.10 Temperatures of the internal and external surfaces and heat gain for double glass air filled window.

Fig.11 shows the variation of the heat gain for double glass windows of thickness of 6 mm and different gaps filled with air. As can be seen the air gap seems to have insignificant effect on the heat gain offering little resistence to heat flow towards the internal space. On the other hand the increase of the glass thickness decreases the heat gain due to the resistence of the glass sheet to and its absorpatance as can be seen in Fig.12.

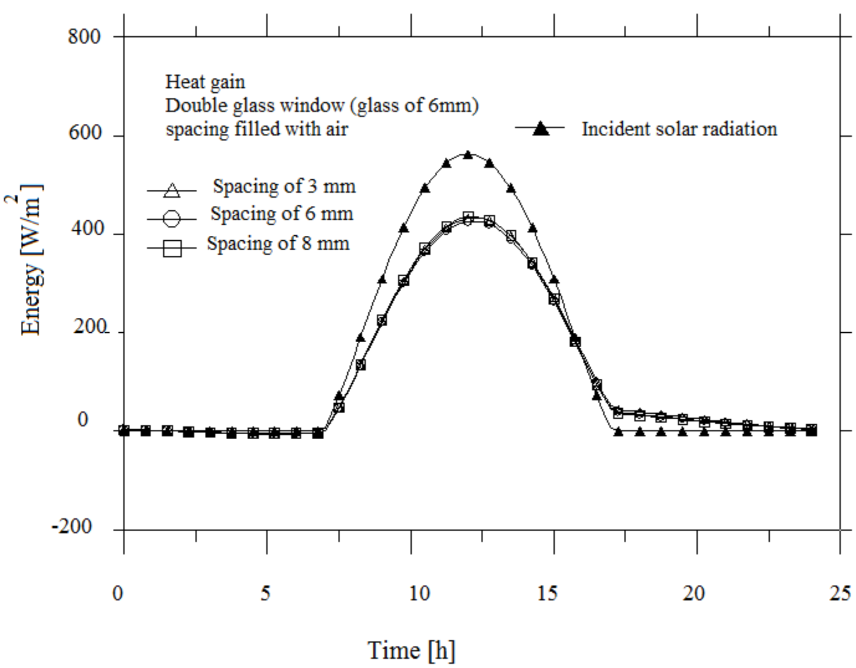

Fig. 11 Variation of heat gain of a double glass air filled window with the air gap width.

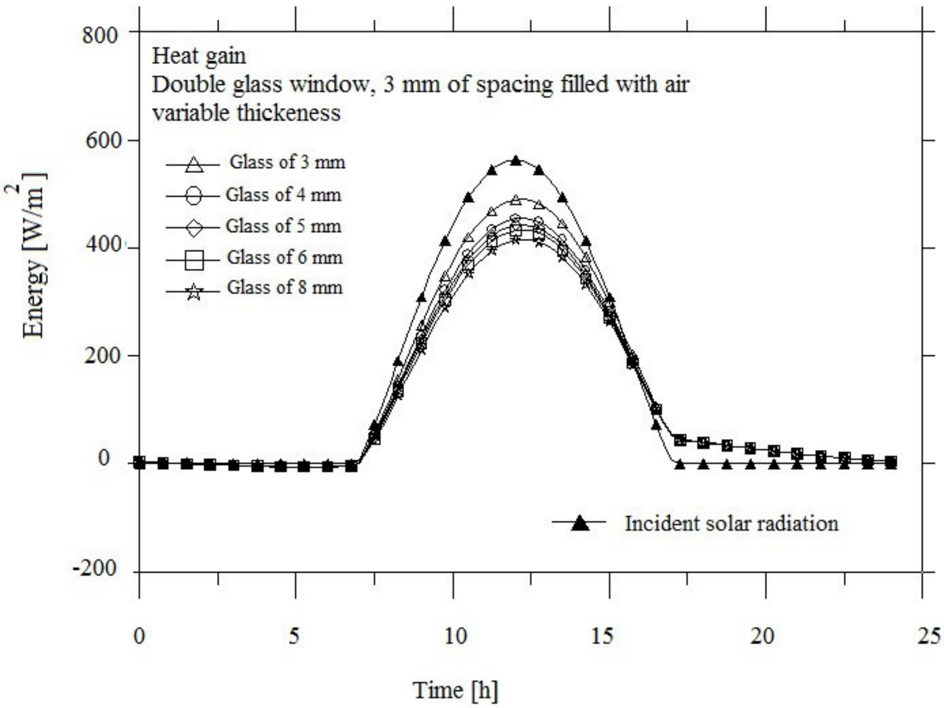

Fig. 12 Variation of heat gain of a double glass air filled window with the glass thickness.

Fig. 13 shows the predictions from the model for the case of 6 mm glass thickness with PCM where the temperature, heat gain and the incident radiation are presented in terms of the solar-time for the city of Campinas, Brazil. As can be seen up to 12 hours the two phases are present. After 12:00 hour, the indoor temperature starts to increase gradually. During the early part of the day the incident heat is used mainly to change PCM solid to liquid and when nearly all PCM is changed to luid its temperature starts to raise. Comparing the results for the window filled with PCM with that filled with air it is possible to conclude that the PCM filling leads to better performance than that with air filling. Fig. 14 shows the reduction of the heat gain due to the increase of the PCM thickness.

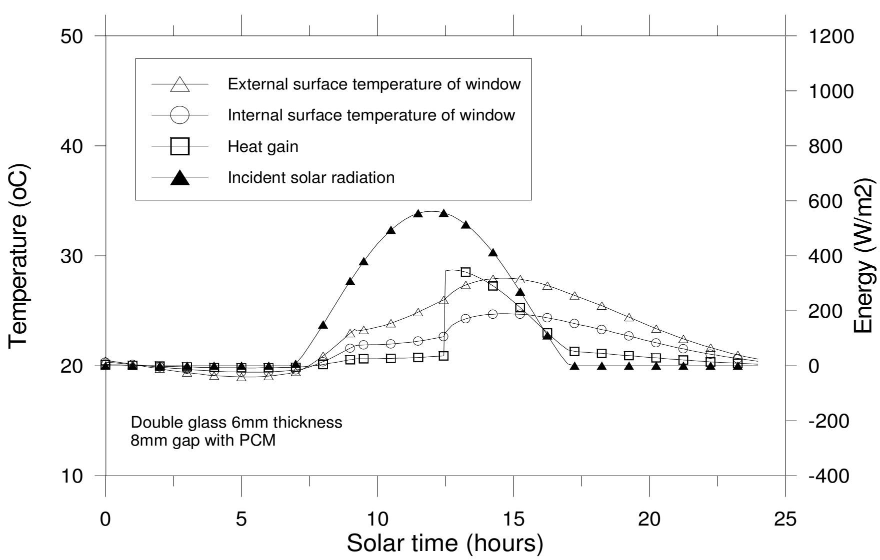

Fig. 13 Model predictions for 8mm gap filled with PCM.

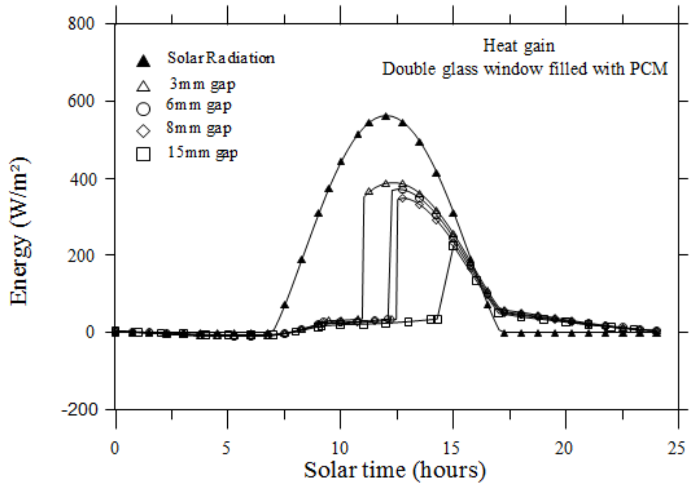

Fig. 14 Heat gain of the double glass window of 6 mm thickness filled with PCM.

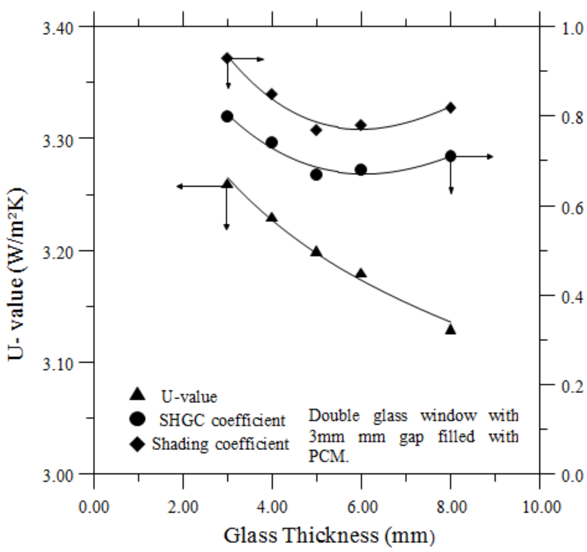

Fig. 15 Variation of U-value, SHGC and Shading coefficients of double glass air filled window with glass thickness.

The results showing the effect of the glass thickness for the case of double glass system are shown in Fig. 15. The value of U seems to decrease continuously with the increase of the glass thickness while the values of solar heat gain coefficient and Shading Coefficient seem to indicate a minimum value at about 5 mm glass thickness.

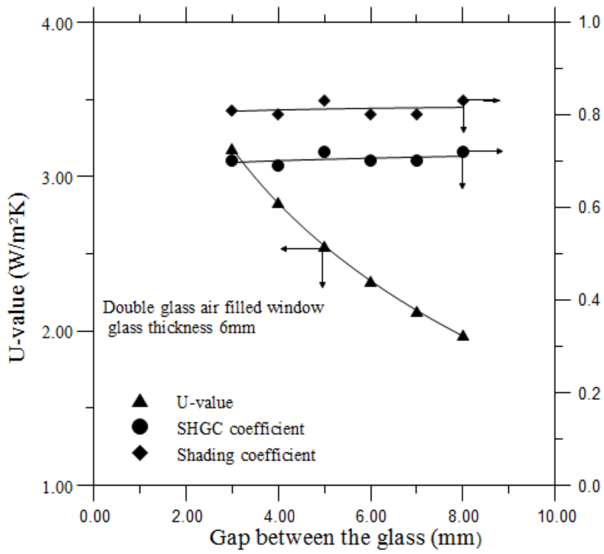

Fig. 16 Variation of U-value, SHGC and Shading coefficients of double glass air filled window with the width of air gap.

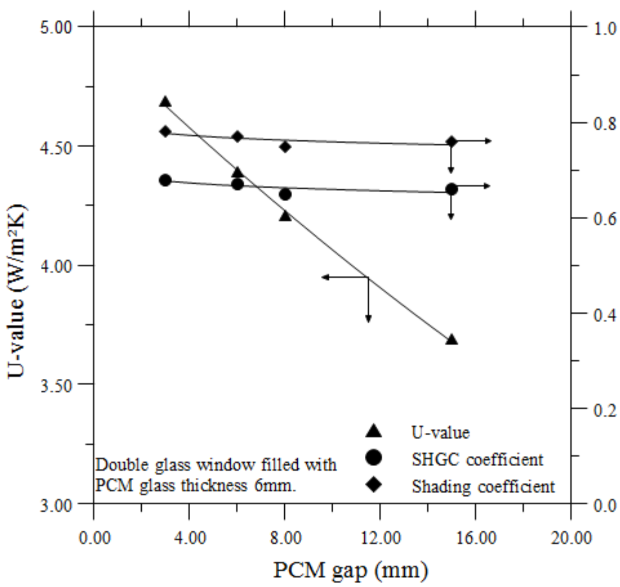

Fig. 17 Variation of U-value, SHGC and Shading coefficients of double glass PCM filled window with the gap width.

Double glass window filled with air indicate a U value decreasing with the increase of the gap width from 3.0 to 2.0 (w/m^2K) as shown in Fig. 16.This is due to the thermal resistence offered by the air layer attenuating the heat and radiation penetration. On the other hand the SHGC and SC values seem to be unaffected by the variation of the gap width.

Fig. 17 shows the results for the case of double glass window with PCM gap filling. Again the U value seems to decrease with the increase of the gap value while the Solar Heat Gain Coefficient and Shading Coefficient SC seem to be unaffected by the increase of the gap between the glass panes.

Some important points in relation to the performance and applications of the PCM filled window gap, need to be clarified. As was described earlier the gap between the glass sheets is filled with PCM which exerts hydrostatic pressure on the glass panes and hence may cause their rupture. This can be solved by fixing glass spacers between the sheets at intervals of about half meter in the vertical direction.

Another important aspect is related to the PCM filling and performance. When filling the gap, the PCM must be in the liquid phase and should be about 5 to 10 % empty to allow for thermal expansion. In case the PCM is being pumped by a small electrical pump, a small hole of about 3 to 4 mm in diameter must be allowed at the top of the system to release the air present in the gap.

One last point to address here is the role of the PCM. The PCM filters the thermal radiation and additionally, by the process of phase change, decreases the amount of penetrating heat until it is totally in the liquid phase.

4. Conclusions

It is found that the increase of the simple window glass thickness increases the thermal resistence and reduces the coefficient of solar heat gain and the coefficient of shading..

Comparison of the results of simple glass window with that of ventilated double glass window it is possible to conclude that the ventilated windows are more efficient and more effective in reducing the heat gain. The need for energy for pumping the air through the gap and the noise and dirt deposited on the inner surfaces of the gap are major disadavantages.

Double glass windows filled with stagnant air are less effective in reducing the heat gain in comparison with the PCM filled glass window. It is also found that increasing the gap filled with air does not change the heat gain of the window.

Double glass windows filled with PCM are found to be effective in reducing the heat gain and increasing the PCM gap thickness is found to improve the thermal performance of these windows.

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