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Numerical thermal model of a double-glazed window filled with phase change materials

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ABSTRACT
Phase change materials (PCMs) glazing systems might be able to improve the building energy performance because of controlling solar heat gains and peak heating and cooling loads. EnergyPlus, a state-of-the-art energy simulation tool, allows simulating the heat transfer through opaque elements that incorporate PCMs. However, EnergyPlus does not allow this for transparent elements with PCMs. As consequence, the main objective of this research is to develop a numerical thermal model of double glazing windows with PCM in the cavity to be coupled with EnergyPlus in the future. To develop the numerical heat transfer model, the sensible and latent heat of the PCM is numerically modelled in MATLAB. This model is used to evaluate the impact of PCM on the inner surface temperature of the window and the Predicted Mean Vote (PMV) in Santiago of Chile. The PCM RT25HC of Rubitherm® shows the better performance because it keeps the internal surface temperature of the window near of the comfort range for more time and the Predicted Mean Vote (PMV) below 1.0.

KEYWORDS
PCM glazing, thermal model, office buildings, PMV.

INTRODUCTION
Central Chile shows a semiarid climate (Bsk according Köppen-Geiger classification) which is characterized by high solar radiation and outdoor temperature during 6 to 8 months. On the other hand, most of office buildings are fully glazed façade office buildings that have very high cooling energy consumption due to high solar heat gains even tough in winter (Bustamante, Vera, Prieto, & Vásquez, 2014).

Phase change materials (PCMs) are able to reduce building cooling loads when incorporated to opaque building envelopes (Ilaria, Lorenza, Goia, & Serra, 2018). However, open floor buildings have low percentage of opaque surfaces. Therefore, there is the opportunity to use windows with PCM to control solar heat gains, daylighting transmission and cooling loads (Giovannini, Goia, Verso, & Serra, 2017; Silva, Vicente, & Rodrigues, 2016). EnergyPlus, a state-of-the-art energy simulation tool, does not include the heat transfer modelling through transparent elements that incorporate PCMs. Otherwise, the heat transfer though opaque elements is well supported by EnergyPlus (Tabares-Velasco, Christensen, & Bianchi, 2012).

Different heat transfer models of the state-of-the-art has the potential to be coupled to an energy modelling software. In particular, Goia et al. (2012) developed a 1D model for heat transfer considering shortwave and longwave radiation heat exchange, conduction and convection. On the other hand, Liu et al. (2016)developed a model considering absorption of the different layers, conduction, convection and radiation of shortwave and longwave transfer. They validated the model with measurements of temperatures.

As consequence, the main objective of this paper is to develop a numerical thermal model of double glazing windows with PCM, which is incorporated in the window's cavity. This numerical model is based on: the main heat transfer equations of Goia et al. (2012) and their nodal distribution to use Crank-Nicolson finite differences method; border conditions according to Liu et al. (2016); PCM' solar properties of Goia et al.(2015); and Tabares-Velasco et al. (2012), where is explained the specific heat calculation of opaque walls based on the relationship between enthalpy and temperature of PCM. To develop the numerical heat transfer model, window properties and the sensible and latent heat of the PCM are numerically modelled in MATLAB. The model is used to determine the best PCM to improve the window' thermal behaviour and thermal comfort of an office space located in Santiago of Chile.

METHODOLOGY

Overall

The process to get the best PCM to improve thermal comfort in an office building in Santiago is carried out in three steps: (i) selection of PCM to be evaluated, (ii) calculation of the mean radiant temperature of the office space using PCM and without PCM by means of a numerical thermal model of heat transfer introduced in this paper, and, (iii) evaluation of the thermal comfort using Predicted Mean Vote (PMV). In the following sections, the building model, climate of Santiago and the heat transfer model are presented.

Building model

The space to be studied corresponds to an office of 6.0 m x 8.0 m x 3.0 m, as shown in Figure 1. A window of 3.0 x 2.0 is oriented north or west. The walls, ceiling and floor are considered adiabatic. Thus, heat transfer only occurs through the glazed façade. The HVAC system consists of an ideal system with heating and cooling thermostat setpoints of 20°C and 25°C, respectively. The internal heat gains are not considered in this case because this study is focused on the heat transfer through the window.

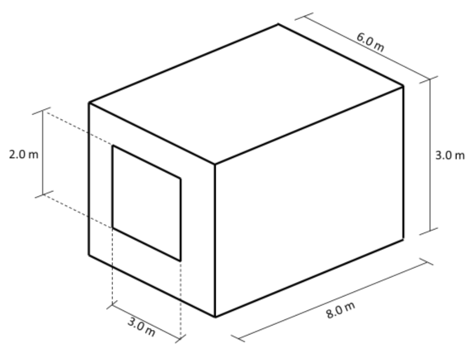


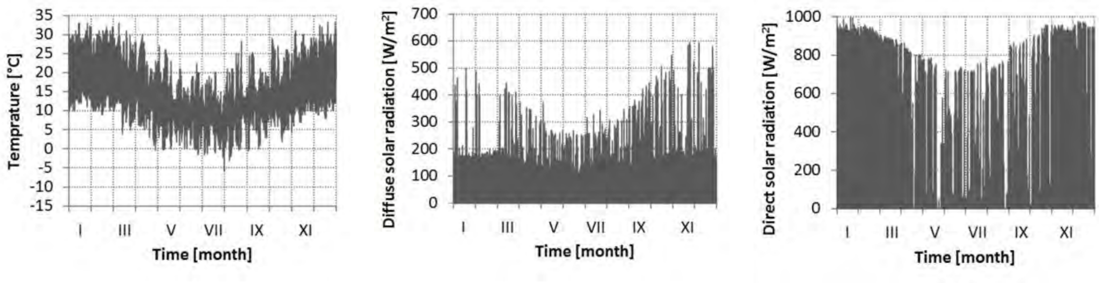
Figure 1. Office space building.

Climate

In Santiago, the highest temperature is 33.2ºC, which occurs in December, and the lowest temperature is in August (-6ºC). The mean outdoor temperature is 14.4ºC. Figure 2a shows the annual air temperature in Santiago. Analysis of solar radiation in Santiago revealed that direct and diffuse solar irradiation are 1632.09 kWh/m2 and 649.48 kWh/m2, respectively. Figures 2b and 2c shows the diffuse and direct solar radiation respectively.

Selection of PCM

PCMs selected are paraffin of the RT Line of Rubitherm company. The melting temperature varies between 12ºC and 35ºC based on the Internal Report of SOLTREN project (Shipkovs et al., 2018). The detailed information about each PCM is presented in Table 1.



(a) (b) (c)

Figure 2. (a) Annual temperature in Santiago. (b) Annual diffuse solar radiation in Santiago. (c) Annual direct solar radiation in Santiago.

Table 1. PCM from Rubitherm® to be studied

PCM	Melting temperature [ºC]	Heat capacity storage [kJ kg^{-1}]
RT12	12	155
RT25	25	170
RT25HC	25	230
RT28HC	28	250
RT31	31	165
RT35	35	160

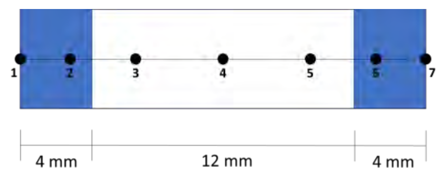


Figure 3. Discretization of thermal model.

Numerical heat transfer model

The heat transfer model has been developed based on model of Goia et al. (2012), Liu et al. (2016), Goia et al. (2015) and Tabares-Velasco et al. (2012). The model consists of a 1D nodal heat transfer of shortwave and longwave radiation, conduction and convection. In this model, 2 nodes are in each glass and 4 nodes in the gap (air or PCM). The discretization scheme is presented in Figure 3.

The model considers the following assumptions: (1) Convection is considerted in the air gap cavity; (2) convection is neglected when the window cavity is filled with PCM; and (3) the absorption through the different layers is considered. Ec. 1 represents the heat transfer through the PCM:

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + \phi \qquad (1)$$

where, t is the time (s), T is the temperature (K), ρ is the density (kg/m^3) and C_p is the specific heat (J/(kg·K)), k is the thermal conductivity, and ϕ is the radiation source term. To solve the equation, Crack-Nicolson finite differences method has been used. The following equations represents the discretization:

$$\frac{\partial T}{\partial t} = \frac{T_i^{n+1} - T_i^n}{\Delta t} \qquad (2)$$

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i-1}^{n+1} - 2T_i^{n+1} + T_{i+1}^{n+1}}{\Delta x^2} \tag{3}$$

where, Δt is the time step, 1 minute in this paper, Δx is the spatial step (m), T_i^n is the temperature in the node i and time n. To this discretization is added the generated radiation. Finally, following is presented the matrix form of the equation to be solved.

$$(I - rA)T^{n+1} = (I + rA)T^n + r(b^n + b^{n+1}) + \phi' \tag{4}$$

Where, I is the identity matrix, A is a matrix of Eq. (5) and b are the remains of the boundary condition also presented in Eq. (5).

$$A = \begin{pmatrix} -2 & 1 & 0 & 0 & & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & & 1 & -2 & 1 \\ 0 & 0 & 0 & 0 & & 0 & 1 & -2 \end{pmatrix} \quad , \quad b = \begin{pmatrix} q_1 \\ 0 \\ \vdots \\ 0 \\ q_2 \end{pmatrix} \tag{5}$$

The numerical thermal model of the heat transfer of the window was implemented in MATLAB. Also, a model of the office space in EnergyPlus was used for calculating the inputs for the MATLAB model. The inputs are the interior mean air temperature, exterior air temperature, the interior and exterior surfaces temperatures of the window, solar radiation and convection parameters.

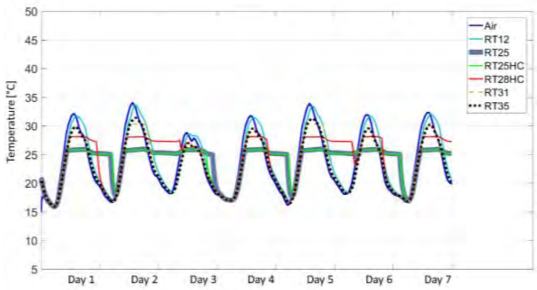
Thermal comfort evaluation

Thermal comfort is evaluated in terms of the Predicted Mean Vote (PMV) (ISO-7730:2005), a mathematical model of a thermal scale that runs from Cold (-3) to Hot (+3) which describe the thermal sensation of occupants.

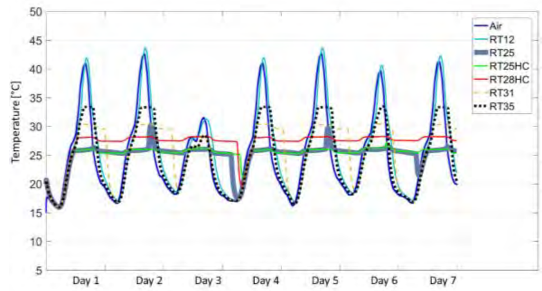
RESULTS

Figures 3 shows the interior surface temperature of the window oriented north and west in a representative summer and winter week, respectively, for all the PCMs evaluated as well as for the window cavity filled with air. Firstly, these results show all peaks of internal window surface temperatures filled with PCM are delayed in comparison with the window filled with air. This effect is due to the difference between the specific heat of the air and PCM. RT12 paraffin is always in liquid state because the temperature in the window is at least 20ºC approximately. When RT25, RT25HC and RT28 paraffin are used in both, north or west façade, they change phase every day, keeping the internal surface temperature constant near to the melting temperature during all working hours. During winter, these three PCMs in north façade are able to keep the internal temperature near to the melting temperature. However, only RT25 and RT25HC are able to change phase in west façade case. The difference of heat storage between RT25 and RT25HC has no relevant effect in this case. Finally, RT31 paraffin changes phase only in summer for both window orientations, and RT35 paraffin never changes phase.

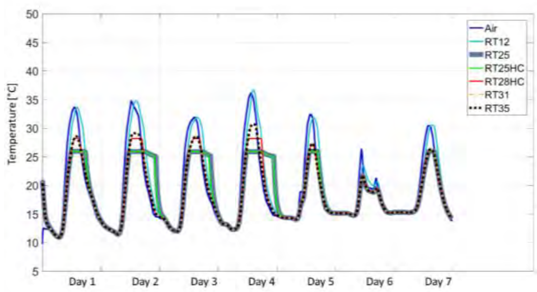
Also, the PCM has a night effect. During summer in the west façade case, the phase change is able to keep the internal surface temperature by two days. To ensure the correct behavior of the PCM glazing, it is needed that the phase change occurs every day. In the morning, the PCM must change to liquid state, and at night must change to solid state. In this case, on day 2, the heat storage is over at the end of the working hours, then, the internal temperature increases, and the thermal comfort of occupants is affected. Due to this, in summer, RT31 and RT35 paraffin have the ability to change phase every day, and in winter, RT25 and RT25HC paraffin show this ability.



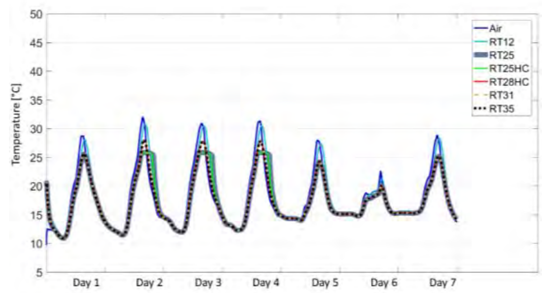
(a) North window façade, summer week



(b) West window façade, summer week



(c) North window façade winter week



(d) West window façade, winter week

Figure 3. Internal window temperatures for a representative week.

Table 2. Mean PMV results for each case

Cavity filling	Summer		Winter	
	North	West	North	West
Air	1.0	1.5	1.1	0.9
RT12	0.9	1.6	1.1	0.9
RT25	0.7	0.9	0.9	0.8
RT25HC	0.7	0.9	0.9	0.8
RT28HC	0.8	1.0	0.9	0.8
RT31	0.8	1.0	1.0	0.8
RT35	0.9	1.1	1.0	0.8

Table 2 shows the mean PMV for the temperature peaks of each day for the representative week of winter and summer. It shows that the PMV for the window filled with air is above or very close to 1.0, which means the indoor environment is slightly hot. On the other hand, PMV value less than 1.0 indicates a comfortable environment. In the north façade for summer, all the PCMs evaluated decrease the PMV below 1.0, but in the west façade, only RT25 and RT25HC decrease the PMV below 1.0. In winter, all PCMs evaluated show PMV values near to 1.0.

CONCLUSIONS

This study developed a heat transfer model of a double-glazed window filled with PCM. The PCMs RT25 and RT25HC have better behavior than the other PCMs because they reduce the inner surface temperature of the windows between 0ºC and 10ºC. As consequences, RT25 and RT25HC allows achieving a comfortable office indoor environment because PMV values are below 1.0. Also, it was found that RT25 and RT25HC does not change phase during summer for 2 days or more, thus the benefits of PCMs are not obtained during these days. Further studies are needed in order to evaluate other climates, whereas future work consists on integrating this model to EnergyPlus to evaluate the impact of windows with PCM on the building energy performance.

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