ENERGY SAVING IN BUILDING USING PCM IN WINDOWS

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ABSTRACT

The significant amount of energy in buildings is consumed by heating and cooling facilities. Reduction of energy loss has always been one of the challengeable issues in building energy management. Windows are considered as a weak link in building constructions and often account for a large percent of a building's energy loss during the summer and winter. One of the promising methods to prevent energy loss through windows is implementing of several layer windows filled with phase change materials (PCM). The objective of this paper is investigation of the effect of using PCM on reduction of energy flow from outdoor space in the summer by absorbing the heat gain in a window through melting process before it reaches the unwanted space during the daytime. Simulation was done using CFD analysis of two types of window with and without PCM for comparison. It is resulted that in window with PCM, phase change material absorbs 86% of exposed heat flux for 9 hours.

INTRODUCTION

Building is one of the principle sectors of the energy consumption. In the year of 2009, around 40% of the total fossil energy was consumed in building sector in the world [1]. Moreover, the energy consumption of heating, ventilation and air conditioning systems is still increasing with the increasing demand for thermal comfort. The importance of insulation materials motivates heat transfer engineers to improve the current technology of the insulation materials used in buildings. Under this circumstance, thermal energy storage systems with high potential to save energy in buildings have gained more and more attention [2]. Thermal energy storage can be generally classified as sensible heat storage and latent heat storage according to the heat storage media. The latent heat thermal energy storage (LHTES) is used extensively in building structures to remove thermal load and to improve the thermal comfort of occupants. For this purpose, latent heat storage with phase change materials (PCM) provides a high heat storage density and has the capability of storing a large amount of heat during the phase change process owing to their high energy densities per unit mass/volume at nearly constant temperatures. Phase change material can be found in different items of the building structure, such as the walls, roof, floor, ceiling, window shutters, plasterboard, and tiles [3].

PCM used in buildings are organic or inorganic substances with low melting temperature. They can be classified as a capacitive type of insulations because they slow down the heat flow by absorbing some of the heat gain. During daytimes, PCM absorb a portion of the heat gain through the melting process, and at night, PCM solidify and releases the stored heat. The net effect is a reduction of heat flow from outdoor to indoor space during the daytime. The selection of PCM is mainly based on its melting temperature, and its chemical characteristics. PCM melting temperature should be within the operating temperature of the thermal system. Low cost, nontoxic, non-flammable, and chemically stable are preferred PCMs.

During the summer season, using PCM in building causes to decrease overall energy consumption by the air conditioning unit as well as time shifting of peak load during the day. Since the variations of solar intensity and outdoor temperature are variable, both the thermal conductivity and the specific heat of the insulation affect the heat flow. In this regard, insulations with low thermal conductivity and high thermal capacity are preferred materials. Among building barriers, windows are known as a weak link in building constructions and often account for a large percent of a building's solar heat gain during the summer [4]. Reducing solar heat gain through windows is clearly one of the keys to reduce energy costs in buildings, especially for buildings with large windows [4].

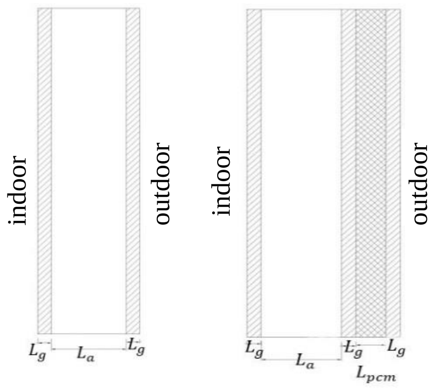
Tiago Silva et al. [5,6] developed window shutter with phase change material and performed some experimental investigation under summer Mediterranean climate conditions. The shutter prototype was applied in an outside cell test composed by two compartments. In their work, window shutter was monitored and analysed the indoor air temperatures, the outside weather conditions and the heat flux of the interior wall partition. V. Dubovsky et al. [7] studied the feasibility of furnishing thermal comfort in a structure with windows, at a mid-storey in a multi-storey building in winter, numerically. In their study, the performance of phase-change paraffin wax

(PCM), as a heat source in winter, was investigated. In an experimental investigation, double glass windows with and without phase change material are tested by W. Rattanongphisat [8]. Experimental results showed that the phase change material acts as a thermal blockage. Int ws revealed that the temperature drop across the double glass pane with phase change material is higher than without using phase change material.

Central part of Iran is subjected in this study due to its warm weather at summer. Hence, in countries with a similar hot climate, results of this study are applicable. In this study, numerical simulation using ANSYS (Fluent) software was performed for a multilayer window. Most researchers which used CFD to simulate the process, reporting a good agreement between the simulation and the experimental results [9]. Here, to prevent flow of heating load of outdoor as well as sun's radiation into the building during summer season, one layer of window is filled with phase change material as an insulation layer.

MODEL DESCRIPTION

The aim of this study is numerical simulation of heat transfer through a window to understand heat load of a building via windows. When outdoor is warmer than indoor building, heat can diffuse in building by convection of hot air at outer layer of window or by radiation of sun. Here, two types of window are considered for applying thermal model: double glass window and a three-glass window which one layer filled with PCM. The schematic of these windows are shown in Fig.1. In this figure, L_g, L_a and L_{PCM} are glass thickness 2mm, argon gap 20mm and PCM thickness 10mm, respectively. The window's height was 1.5 m. In this model, the outdoor surface is subjected to force convection of outdoor warm air as well as solar radiation, whiles the indoor surface of the glass is subjected to free convection boundary condition.



a) type I b) type II

Fig 1 Schematic of window's layer a)type I, double glass window, and b) type II, window with PCM

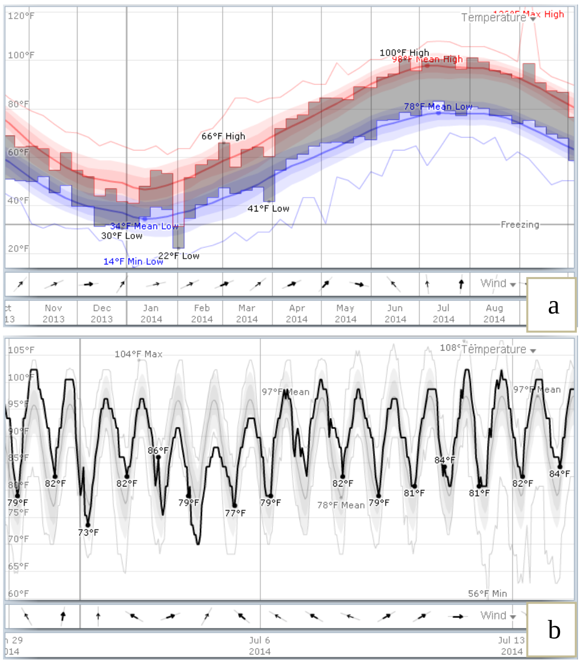


Fig 2 Climate temperature of Tehran, Iran a) yearly and b) daily

Heat transfer in window is three-dimensional, in fact, however the width and length of window is large enough compare to window's thickness. Therefore, by neglect of the end effect of window, thermal model of window is considered with two-dimensional simulation.

In order to thermal modelling, the climate temperature data for the hottest month of year e.i. July for Tehran city in Iran are collected using climate agency [10] and depicted in Fig. 2. In summer, the comfort indoor room temperature of a building can be selected with regards to level of comfort and room application from tables in ASHREA standard [11,12]. Here, we consider a residential room which comfort room temperature is T_{in}=296.5 K. This temperature is subjected to indoor condition of window's wall, which causes free convection heat removal from windows at summer. On the opposite side of window, climate temperature is varied during a day time as shown in Fig 2. The temperature difference of both side of the window causes thermal diffusion through glass/PCM and leads to provide natural convetion in argon gap. With considering the above assumption, the governing two-dimensional equations in thermal model of a window can be written as follow:

In argon gap:

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

X momentum:

$$\rho_a\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\frac{-\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

Y momentum:

$$\rho_a\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=\frac{-\partial P}{\partial y}+\mu_a\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho\beta g(T-T_{ref}) \quad (3)$$

Energy:

$$(\rho c)_a\frac{\partial T_a}{\partial t}=k_a\left(\frac{\partial^2 T_a}{\partial x^2}+\frac{\partial^2 T_a}{\partial y^2}\right) \quad (4)$$

Where *u* and *v* are velocity, T_a is temperature and ρ_a, μ_a and k_a are density, viscosity and thermal conductivity of argon, respectively.

In PCM and glass, we need to identify the temperature distribution. In this model if we neglect the natural convection of PCM, energy equations for these parts are as follow:

Glass energy:

$$(\rho c)_g\frac{\partial T_g}{\partial t}=k_g\left(\frac{\partial^2 T_g}{\partial x^2}+\frac{\partial^2 T_g}{\partial y^2}\right) \quad (5)$$

PCM energy:

$$(\rho c)_{pcm}\frac{\partial T_{pcm}}{\partial t}=k_{pcm}\left(\frac{\partial^2 T_{pcm}}{\partial x^2}+\frac{\partial^2 T_{pcm}}{\partial y^2}\right) \quad (6)$$

The subscript a, g and PCM dented to argon, glass and phase change material, respectively. In accordance with the model geometry and above equations, boundary conditions are described as below:

On glass surface subjected to indoor condition of room, we assumed that the free heat convection is known. Therefore:

$$x=0\ \&\ 0<y<H: \quad (7)$$

$$-K_g\frac{\partial T_g}{\partial x}=h_i(T_i-T_{is})$$

Where, h_i is heat transfer coefficient, obtained from ASHREA handbook. At the interface of glass-argon and glass-PCM, the heat flux is identical:

$$x=L_g\ \&\ 0<y<H: \quad (8)$$

$$K_g\frac{\partial T_g}{\partial x}=K_a\frac{\partial T_a}{\partial x}$$

$$x=L_g+L_a\ \&\ 0<y<H: \quad (9)$$

$$K_a\frac{\partial T_a}{\partial x}=K_{pcm}\frac{\partial T_{pcm}}{\partial x}$$

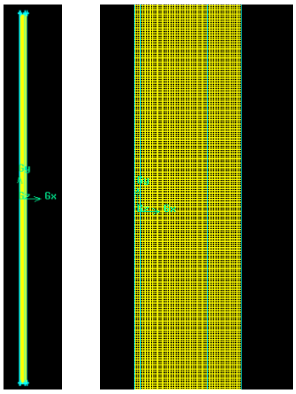


Fig 3 Window's geometry and structured mesh in Gambit

On the outside of window's glass subjected to outdoor, force convection and radiation are assumed to be known:

$$x=L_g+L_a+L_{pcm}\ \&\ 0<y<H: \quad (10)$$

$$-K_{pcm}\frac{\partial T_{pcm}}{\partial x}=h_0(T_0-T_{pcm,s})$$

$$-K_{pcm}\frac{\partial T_{pcm}}{\partial x}=\sigma A(T^4-T_{surr}^4)$$

Where h_0 and σ are outdoor heat transfer coefficient and Stefan Boltzmann constant, respectively.

NUMERICAL MODEL DESCRIPTION

In order to solve PDE equations numerically, it is necessary to discrete equation by some discretization method. In this study, CFD model and calculation was performed in ANSYS (Fluent) well known as a powerful commercial software. It is based on finite volume method. The geometry and structured mesh was produced in Gambit, and it is demonstrated in Fig. 3.

Based on enthalpy of the material, Fluent can model solidification and melting of PCM. The enthalpy of the material is computed as the sum of the sensible enthalpy, h, and the latent heat ΔH:

$$H=h+\Delta H \quad (11)$$

$$h=h_{ref}+\int_{T_{ref}}^{T}C_p\,dT \quad (12)$$

Where, h_{ref}, T_{ref} and C_p are reference enthalpy, reference temperature and specific heat at constant pressure, respectively. In this regards, the liquid fraction β can be defined as:

$$\beta=0 \text{ if } T<T_s \quad (13)$$

$$\beta=1 \text{ if } T>T_l$$

$$\beta=\frac{T-T_s}{T_l-T_s} \text{ if } T_s<T<T_l$$

Therefore, the latent heat content can now be written in terms of the latent heat of the material:

$$\Delta H = \beta L \qquad (14)$$

Hence, it can vary between zero (for a solid) and L (for a liquid).

For solidification/melting problems, the energy equation is written as below:

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho\vec{v}H) = \nabla.(k\nabla T) + s \qquad (15)$$

Where, H, ρ, $\vec{v}$ and s are enthalpy, density, fluid velocity and source term, respectively.

The enthalpy-porosity technique treats the mushy region (partially solidified region) as a porous medium. The porosity in each cell is set equal to the liquid fraction in that cell. In fully solidified regions, the porosity is equal to zero, which extinguishes the velocities in these regions. In this particular case, PCM in window is assumed as stationary material. Therefore, fluid velocity can be neglected.

RESULT AND DISCUSSION

In regard with average temperature of ambient, 310 K, and the comfort temperature of room, 296.5 K, the phase change material, was chosen so that the melting temperature is lower than 310 K but greater than 296.5 K. In this study, PCM is n-octadecane with chemical formula $C_{18}H_{38}$, which that melting temperature is 301K.

According to these criteria, heat is removed from inner glass exposed to room condition via natural convection. The best solution for natural convection can be done in Fluent using density-based model. On the opposite side, The solidification/melting model can be performed by applying the pressure-based model. To overcome this conflict, the pressure based model was selected as a solver model.

Mean outdoor temperature T_{out}=310 K with slow wind causes forced heat transfer on outdoor of window glass. In accordance with ASHREA heating, ventilation and air conditioning handbook [12], the heat transfer coefficient considered in this model is 5 W/m^2K.

The aim of this study is obtaining the difference of heat flux diffusion from ambient into the room in summer, in regard with window's type. In this way, constant heat flux was applied on the outer window's wall started from 7 O'clock in the morning. The model was run in Fluent, unsteadily. The total heat flux applied on the outer window wall consist of radiation heat flux, $q"_r$, and convection heat flux, $q"_c$:

$$q"_t = q"_r + q"_c \qquad (16)$$

From ASHREA fundamental handbook $q"_r$ and $q"_c$ are:

$$\begin{aligned} q"_r &= solar\ heat\ gain \times correction\ factor \\ &\quad \times storage\ coefficient \\ &= 24 \times 0.56 \times 0.63 \\ &= 8.5\ {}^{Btu}/_{hr.ft^2} \\ &= 26.7\ W/m^2 \end{aligned} \qquad (17)$$

$$\begin{aligned} q"_c = h(T_s - T_\infty) &= 5(310 - 301) \\ &= 45W/m^2 \end{aligned} \qquad (18)$$

Therefore, the total heat flux is 71.7 W/m^2. This is maximum heat flux of outdoor window's wall. The specification of argon, glass and PCM are listed in Table 1.

Two types of window, as were shown in Fig. 1, are considered in this work: double glass window and window with PCM layer. The results obtained for two types of window are discussed here, separately:

Table 1 material specifications

Material	k W/m K	C_p J/kg K	ρ Kg/m^3
Argon	0.158	520.64	1.6228
PCM(*l*)	0.15	2210	774
Glass	0.7	750	2800

a)

b)

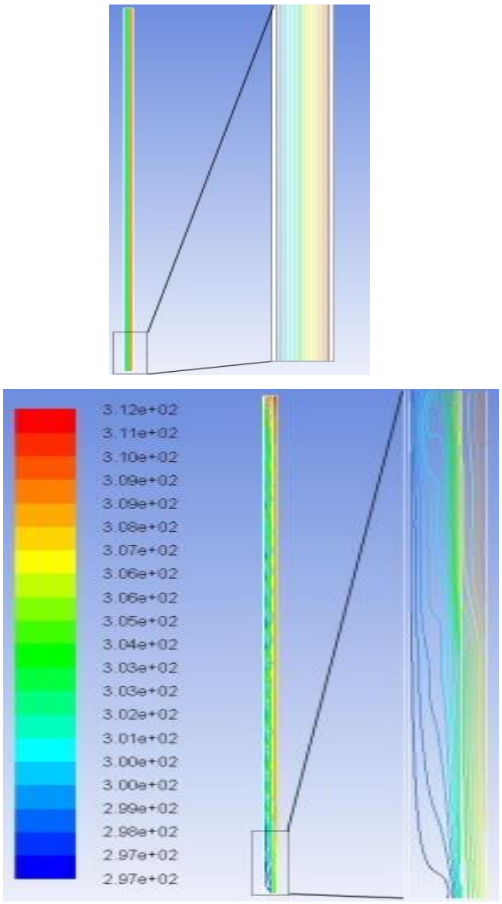


Fig. 4 Contour of temperature, a) type I window, b) type II window

Type I: the type I is double glass window. This type of window, have an argon gap which is a good barrier between indoor and outdoor of a building. However, as long as outdoor temperature rises during daytime, diffusion of heat from outside to inside of a building increases, gradually. Contour of temperature for this type is depicted in Fig. 4. Heat flux which is entered into the room can be obtained during daytime. Fig. 6 show the variation of heat flux diffusion during daytime. It can be seen that, after 6 hours (12 O'clock) more than 97 percent of outdoor heat flux came into the building from type I window.

Type II: outer layer of this type of window, is filled with PCM. This type of PCM is generally non-toxic and hence it can be used in human environment without major hazardous danger. The melting temperature of this kind of PCM is 301 K, which can be met during daytime. In the course of melting, heat stored in the PCM in constant temperature, and it inhibits to flow heat load into the building. It is supposed that the initial condition of the PCM, at 7 O'clock in the morning is solid manner with comfort temperature 296.5 K. Liquid fraction of PCM was shown in Fig. 5, at 7, 10, 13 and 16 O'clock.

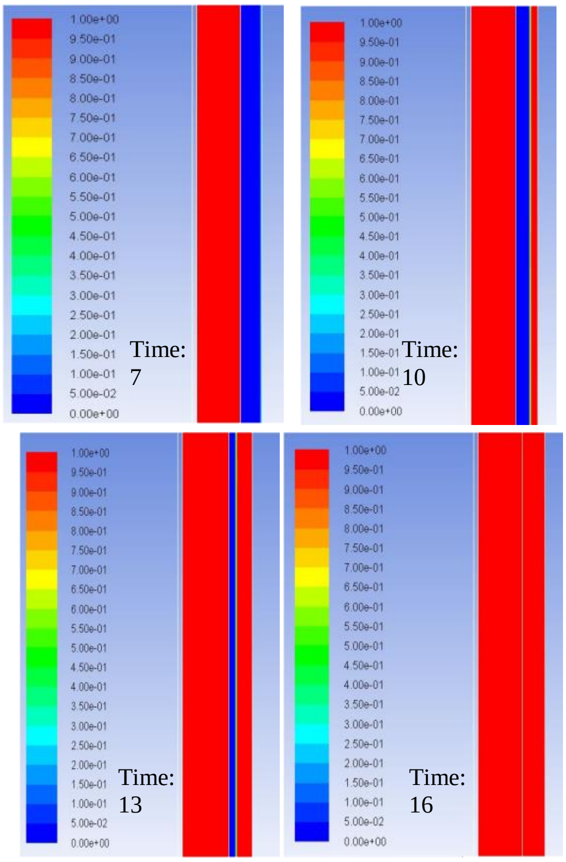


Fig. 5 Contour of liquid fraction of window with PCM

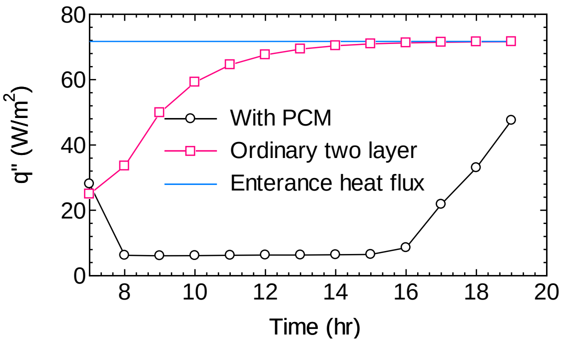


Fig. 6 Heat flux entered in room via two different windows

According to this figure, PCM will be in total liquid state at 16 O'clock. Therefore, PCM can store most of applied heat flux from 7 to 16 O'clock, and inhibit of heat diffusion into the building. At night time, phase change from liquid to solid can hand over heat energy, again and this cycle can be repeat for next day.

In Fig. 6, it is seen that diffusion heat flux into the room is approximately constant at 9.7 W/m^2 during phase change of PCM from solid to liquid. The completely melting process of PCM take 8 hours, which is the period of warm time of a day in summer season in Tehran. With the marginal assumption, that outer wall of window is imposed of constant of maximum heat flux during a day, it is seen that after completely melting of PCM, heat flux increases, monotonically.

CONCLUSION

Windows are known as weak thermal barriers of building that make significant heating or cooling load on the utilization facilities of a building. This week part can be thermally reinforced by adding one layer with an argon gap. In this study, we added one more blockage layer subjected to outside layer, filled with phase change material.

Phase change materials are a substance that using to implement high latent heat capacity by melting process. Here, it was tried to use PCM in window as a heating storage to slow down heat flux diffusion into the building. In this study, heat flux diffusion from outside to inside of a building though two types of window was compared during a summer day in Tehran, Iran. Type I, is double glass window and type II is three-glass which one layer is filled with PCM. In type I, heat flux diffusion into the room increases monotonically along daytime, and after 6 hours it reach to 97% of applied heat flux. On the other hand, for type II, it is found that the most of heat flux absorbed by PCM and prevent to diffuse into the room. According to numerical simulation performed by Fluent, it is resulted that in type II window, PCM hold 86% of outdoor heat flux into the window for 9 hours. Hence, it is concluded that, using PCM in windows can make a good thermal barrier in summer in windows of a building.

NOMENCLATURE

A = Area
a = *argon*
H = Window Height
h = Heat Transfer Coefficient
k = Thermal Conductivity
L_g = Glass Thickness
L_a = Gap Thickness
L_{pcm} = Phase Change Material Thickness
q'' = Heat Flux
t = Time
x = Lentgh Parameter
y = Lentgh Parameter
z = Lentgh Parameter
σ = Stephan Boltzman Constant

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