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ASSESSMENT OF BUILDING ENERGY EFFICIENCY WITH SMART WINDOW GLAZING CURTAIN WALLS

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ABSTRACT

The purpose of this paper is to investigate the potential of diminishing the energy consumed for heating, cooling and lighting buildings using smart windows. The windows considered consisted of a double pane glazing unit in which an absorbing layer is added on the interior surface of the exterior glass pane. This absorbing layer allows to change the optical properties of the window, resulting in a direct potential of control of the incident solar heat flux entering the building through the windows. In this paper, a numerical model is developed and it is shown that optimizing the solar heat flux absorption rate of the absorbing layer in regard of the necessary heating, cooling and lighting demands helps reducing significantly the total yearly energy consumption, and cooling peak loads.

Keywords: Smart windows, switchable glazing, heat transfer, solar radiation, daylighting, energy load calculation, building energy efficiency.

INTRODUCTION

Since environment protection is now an unavoidable subject, it has become a priority to reduce our energy consumption. Buildings, consuming more than one third of the overall energy worldwide, present a huge potential of energy consumption reduction [1]. Over the last years, building design has been oriented toward the optimization of energy usage, the protection of the environment and the occupants' comfort. On the other hand, current urban development involves the construction of large office buildings with huge percentage of glazed areas. This architectural trend involves important challenges with respect to the reduction of building energy consumption since glazing constitutes one of the less efficient components of the building envelope energywise.

The poor energy efficiency of glazing compared to the other components of the envelope offers great opportunities to develop new glazing technologies that are more energy efficient. There already exist emerging technologies aiming to improve glazing performances in regard to environment, energy consumption and comfort. Among these technologies are smart windows that manage solar heat flux entering buildings by controlling the glazing opacity, "aerogel" glazing [2] that provides a very high heat transfer conduction resistance and ventilated photovoltaic glazing [3] that limits heat transfer with the help of controlled convection and supplies an additional amount of renewable energy. Smart windows are defined as glass technologies whose optical properties change when a voltage is applied. Electrochromic [4] and liquid crystals [5] glazings are two main examples of smart window technologies.

The technologies offering the highest potential of adaptation in regards to solar radiation are the smart windows [6]. Since solar radiation represents a huge contribution to the building overall energy balance, further studies on smart windows might result in important breakthroughs in building energy efficiency improvement. This article presents the modeling of a simplified building with integrated smart window glazing and the results of opacity optimization to achieve minimal energy consumption.

SMART WINDOW GLAZING IN SOLAR RADIATION CONTROL

As mentioned above, different types of smart window technologies exist. These technologies have their own optical properties that can vary significantly from one another. Among these optical properties, the way of controlling how much solar radiation penetrates the building has probably the most impact on the resulting building energy consumption. For instance, some smart window technologies control solar radiation by absorption while others control it by reflection or, less efficiently, by scattering. For example, polymer dispersed liquid crystals (PDLC) smart windows scatter light passing through because of the difference of refraction index between polymers and liquid crystal droplets forming the liquid crystal layer. The liquid crystal layer is held in place by two transparent conductive layers, generally made of ITO. When a voltage is applied between the ITO layers, liquid crystals tend to align with the electric field. This creates a media of uniform index of refraction that allows light to pass without scattering.

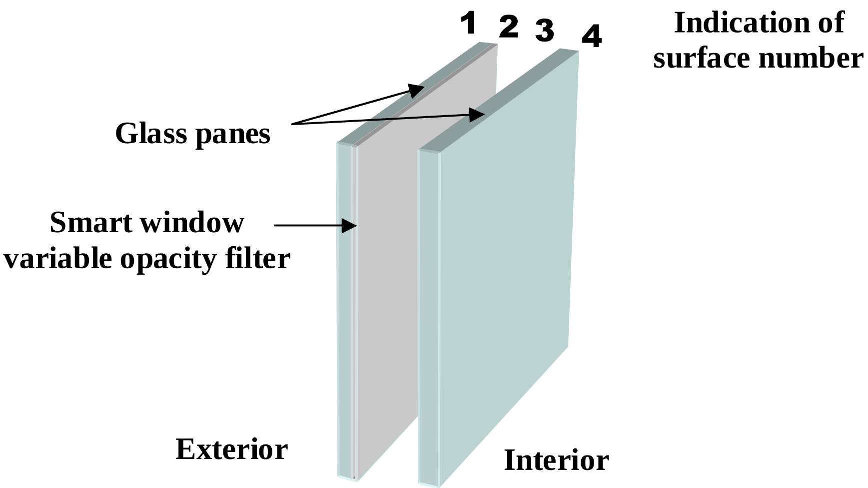

Fig. 1: Double glazed smart window

Since the purpose of this paper is to present the potential of smart window glazing in general, we will focus our attention on a generic smart window controlling solar radiation by absorption rather than working with a specific smart window technology. This control is achieved with a variable opacity filter inserted in-between the glass panes. In the present case, the term “opacity” refers to the solar absorption rate of the filter. In the glazing industry, each glass pane surface is given a number in relation to its order, starting from the exterior surface. Fig. 1 illustrates the surface indices of a double glazed window and the surface on which the opacity filter is fixed on (surface 2).

As shown in Fig. 1, the variable opacity filter is fixed to the inner surface of the outer glass pane (surface 2). This decision is taken mainly for two reasons. First, the filter needs to be installed on an inner surface (2 or 3) for protection (e.g., against direct UV, scratching, etc.). Second, during solar radiation peak hours in summer, the filter will absorb a huge amount of energy resulting in an important increase of the filter temperature. Due to higher exterior convection coefficient, it will be easier to dissipate the heat outside of the building with a hot surface 2 than it would have been with a hot surface 3. This way, we assure a more reasonable range of temperature operation for the variable opacity filter. A variable opacity filter fixed on surface 3 and having a high temperature may also cause discomfort for occupants close to windows.

Finally, for opacity changes, smart windows require an electric potential. In other words, we need to provide electrical energy to smart windows in order to reduce the overall energy consumption. Fortunately, the amount of electrical energy required to operate the variable opacity filter can be negligible. Also, different renewable energy sources could be use for energy supply such as window frame integrated photovoltaic panels. For these reasons, smart window energy consumption will be omitted in the present case study.

MODELING

The advantage of smart windows is their ability to adapt to the exterior and interior conditions in order to reduce the resulting building energy consumption and/or peak loads. The control of a smart window to reduce overall energy consumption involves a tradeoff between the energy required for heating and that required for lighting, since preventing solar radiation from penetrating within the building reduces the heating requirement (beneficial) but might also call for more lighting (detrimental). Therefore, the following sub-sections describe the model developed to determine the heat transfer rate between the building and the environment through a smart window, and the model developed to establish the daylight level on workplanes depending on window features.

Heat transfer balance modeling

The goal of the thermal model is to calculate the total heat load (Q_{HVAC}) that the heating, ventilating and air conditioning (HVAC) system must supply to keep the inside air temperature at a set-point value for a typical office building zone. Modeling and analysis have been performed with Matlab.

The building zone considered consists of a single room with one totally glazed external wall (ε_{window}=0.84), and 5 internal surfaces (i.e., 3 internal walls, a floor and a ceiling) which are assumed not to exchange heat with the other building zones nor with the exterior (ε_{surf}=0.9). The model also considers a thermal mass included in the 50.8 mm thick floor slab (ρ_{floor}=2400 [kg/m^3], $c_{p,floor}$=1085 J/kgK). The room dimensions are 5 m width by 5 m deep by 3 m high. For simplicity, the interior walls and the ceiling are assumed to be at the same temperature as the interior air, T_{walls} =T_{in}=20 °C. The exterior wall is a double glazed window (k_{glass}=1.38 W/mK) with a 6.3 mm thin air gap (k_{air}=0.024069 W/mK, α_{air}=17.64×10^{-6} m^2/s, γ_{air}=21×10^{-6} m^2/s).

Solar radiation had been modeled considering that the exterior wall faces south and that the building is located in Quebec City, Canada, i.e.: latitude = 47° North, longitude = 71° West. Furthermore, the glass slabs constituting the external glazed wall are clear glass (no added tint or low emission layers) for a matter of clearly isolating the effect of the variable opacity filter. The model assumes that the direct solar radiation passing through the window is distributed uniformly over the floor area and the diffuse solar radiation is distributed over the floor, ceiling and internal walls weighted by the appropriate view factors. Moreover, solar radiation is assumed to be totally absorbed by internal surfaces and then reemitted in the infrared wavelengths, meaning that the window is considered as an opaque surface for internal radiation. Also, since internal walls and ceiling are at the same temperature, they are considered as a single surface in the radiation balance calculations. Solar radiation entering the building is then accounted in the overall energy balance in the form of additional heat sources applied to the glazing ($Q_{solar\ glazing}$), to the walls/ceiling surface ($Q_{solar\ walls}$) and to the floor ($Q_{solar\ floor}$).

The external glazed wall is subject to exterior convection, h_{out}=14 W/m^2K [7], and external temperature variations depending on the hour of the day and the day of the year. The exterior temperatures used for the calculations are the ones for the year 1995 found in the eQUEST 3-63 weather database. The interior walls and ceiling are subject to interior convection, h_{in}=8 W/m^2K, and the air-to-floor convection coefficient is h_{floor}=1 W/m^2K.

For simplicity, the main modeling assumptions are:
1- 1D heat transfer through the glazed wall
2- No window frame has been considered
3- There are no thermal bridges in the building envelope

4- No spectral consideration for material properties
5- The variable opacity filter is assumed to have no angular optical properties dependence
6- All interior surfaces are adiabatic, i.e. no exchange with other zones of the building
7- Interior surfaces reflect radiation diffusely
8- The room occupancy is 3 persons
9- Interior air temperature is constant throughout the year
10- Latent load is not considered
11- The only thermal mass considered is that of the floor

Fig. 2 shows a thermal circuit of the system considering thermal nodes ($T_{...}$), thermal resistances ($R_{...}$), thermal mass (C_{floor}) and internal heat sources ($Q_{...}$)

The methodology used to obtain Q_{HVAC} consists in performing an energy balance at each node of the circuit, grouping the resulting equations into a matrix equation, and solving for the unknowns (i.e., $T_{s,out}$, T_1, T_2, $T_{s,in}$, Q_{HVAC} and T_{floor}).

The thermal effect of lighting separates in two distinct phenomena, i.e.: a portion of energy required for lighting is directly transformed into heat transferred to the room ($Q_{light,\ conv}$) while the other portion corresponds to the radiation emitted by the lighting devices ($Q_{light,\ rad\ walls}$ and $Q_{light,\ rad\ floor}$). Depending of the lighting device, convective and radiative portions will be different. In this study, we will consider standard fluorescent tubes with 59% of radiative lighting and 41% of convective lighting with fixtures having a 20% heat-to-return [8]. In order to determine radiative heat flux reaching each internal surface, we assume a total lighting power spread uniformly over the ceiling surface and emitted diffusely. The total artificial lighting power considered for calculation is 586.3 W. This value guarantees that the minimum luminance value is respected during occupancy hours.

The other internal heat gains are from occupants and miscellaneous equipments. For both these gains, we considered 30% of convective heat gain ($Q_{occupants,\ conv}$ and $Q_{miscellaneous,\ conv}$) and 70% of radiative heat gain ($Q_{occupants,\ rad\ walls}$, $Q_{occupants,\ rad\ floor}$, $Q_{miscellaneous,\ rad\ walls}$, and $Q_{miscellaneous,\ rad\ floor}$). Each occupant is assumed to generate a total of 73 W and we supposed a miscellaneous equipment power surface density of $8 W/m^2$.

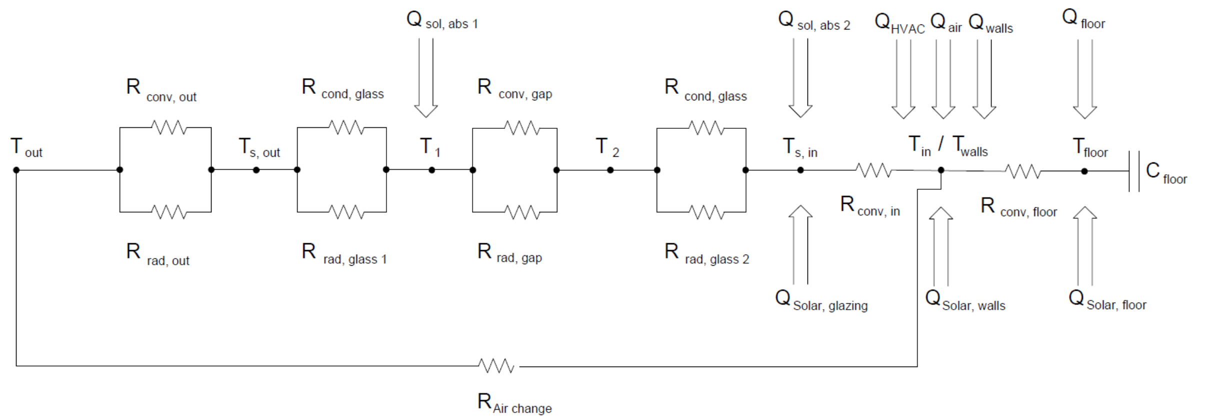

Fig. 2: Thermal circuit representation of the building with a smart window

Internal heat gains are represented in Fig. 2 by Q_{air}, Q_{walls} and Q_{floor}. These quantities are related by:

$$Q_{air} = Q_{light,conv} + Q_{occupants,conv} + Q_{miscellaneous,conv} \tag{1}$$

$$Q_{walls} = Q_{light,rad\_walls} + Q_{occupants,rad\_walls} + Q_{miscellaneous,rad\_walls} \tag{2}$$

$$Q_{floor} = Q_{light,rad\_floor} + Q_{occupants,rad\_floor} + Q_{miscellaneous,rad\_floor} \tag{3}$$

The schedule for internal heat gains follow the occupancy hours that are from 8 AM to 5 PM.

The makeup air is represented in Fig. 2 by the air change resistance ($R_{Air\ change}$) and considers a rate of 20 cfm/person necessary during occupancy hours. Furthermore, a heat exchanger had been considered with an efficiency of heat recovery of 40%.

Solar absorption by the glazing panes and variable opacity filter is represented in Fig. 2 by $Q_{sol,\ abs1}$ and $Q_{sol,\ abs\ 2}$. Their relations are the following:

$$Q_{sol,abs1} = (\alpha_{pane1} + \alpha_{filter}) Q_{solar} \tag{4}$$

$$Q_{sol,abs2} = \alpha_{pane2} (Q_{solar} - Q_{sol,abs1}) \tag{5}$$

where α_{pane1} and α_{pane2} correspond to absorption rates of the exterior and interior window glass panes, respectively, α_{filter} to the absorption rate of the variable opacity filter and Q_{solar} to the total incident solar radiation power.

Daylight modeling

The daylight model allows to evaluate the amount of visible solar irradiation incident on the plane of interest. In the present case, the global solar luminance in the room, L_S, is calculated on the floor with the following relation:

$$L_d = K_d \tau_d G_d F_{window/floor} \qquad L_D = \frac{K_D \tau_D G_D A_{Directly\_lighted}}{A_{floor}} \qquad L_S = L_D + L_d \tag{6}$$

where L_d and L_D are the diffuse luminance and direct luminance, respectively. The value used for the diffuse luminous efficacy (K_d) is 123 lumen/W and for the direct luminous efficacy (K_D) is 102 lumen/W [9]. τ_d and τ_D are the overall transmission coefficients for diffuse and direct irradiations, G_d and G_D, the diffuse and direct solar irradiations, $F_{window/floor}$, the view factor from the glazed wall to the floor and $A_{Directly\ lighted}$ and A_{floor}, the surfaces of the floor area lighted by direct sunlight and the total floor area, respectively. The overall transmission coefficients mentioned above are obtained by:

$$\tau_d = \tau_{glazing,d}(1 - \alpha_{filter}) \qquad \tau_D = \tau_{glazing,D}(1 - \alpha_{filter}) \tag{7}$$

where $\tau_{glazing,d}$ and $\tau_{glazing,D}$ are the transmission coefficient for diffuse and direct solar irradiations, not considering the variable opacity filter.

The main assumptions for the daylight model are:

1- Direct luminance is spread uniformly over the entire floor area
2- Diffuse luminance falls on each interior surface uniformly
3- There is no spectral consideration for material properties
4- Daylight reflections into the room are not considered

MODELS VALIDATION

This paper presents results of smart window opacity optimization to reduce the global building energy consumption. In order to obtain valid results, one must evaluate the performance of the given models to represent realistic situations. To do so, the energy balance model was compared with the extensively validated building energy simulation software eQUEST 3-63.

Results have been obtained in eQUEST 3-63 modeling a building with properties that where as close as possible to the ones used in the heat transfer model with α_{filter}=0. Hour-by-hour results have been achieved for an entire year. To present these results in a convenient way, averages for each hour of the day for each month of the year have been calculated and are presented in Fig.3. For example, the horizontal arrow in Fig. 3 illustrates the time range for an average day of February.

Fig. 3 shows that results obtained with the heat transfer model are in good agreement with results obtained with eQUEST 3-63. Maximal differences between the two curves are of the order of 10% in heating conditions and 2% in cooling conditions. These differences can be explained by the different model assumptions. For example, eQUEST 3-63 considers thermal mass in every material even if the value is small versus the present heat transfer model that takes into account only the thermal mass of the floor slab. Also, the heat transfer model assumes that the solar energy absorbed by glass panes 1 and 2 is concentrated on surfaces 2 and 4, respectively, resulting in a more important heat transfer toward the interior. This effect can be seen in Fig. 3 by the results of the heat transfer model that are slightly lower than the

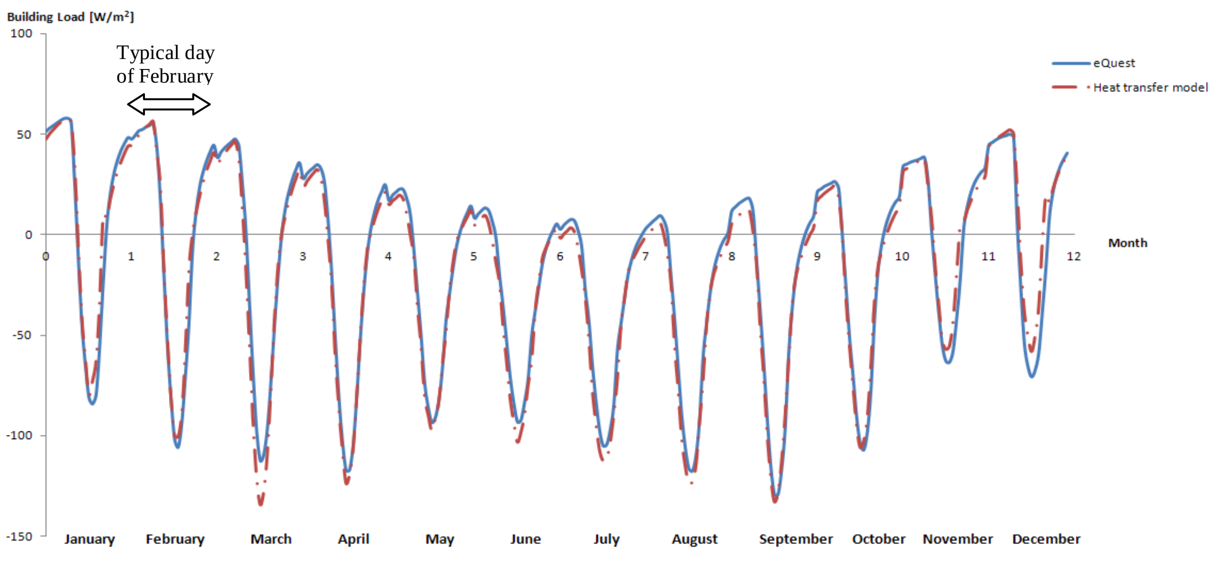

Fig. 3: Daily building mean total sensible load for each month of the year.

ones obtained by eQUEST 3-63 which is more easily observed between March and September when solar radiation is of greater importance. Nevertheless, since the goal of this paper is to assess the performance of a new building envelope technology and because of the simplicity of the model, perfect agreement with eQUEST 3-63 is not required at this point.

The daylight model presented in this paper has been kept very simple since, in the present research, the emphasis is on the energy consumption reduction rather than on the detailed distribution of visible light on workplane. Nevertheless, the model gives a realistic representation of interior solar luminance and the order of magnitude of the daylight results have been verified, which is required to obtain valuable results. Further works will focused on the integration of a more sophisticated daylight model into the energy efficiency building optimization.

RESULTS ANALYSIS

The potential for energy reduction varies with weather conditions. To assess the performance of the smart window glazing technology, optimization runs have been performed for a complete week of each season, i.e.: winter (1^{st} to 7^{th} of January), spring (1^{st} to 7^{th} of April), summer (1^{st} to 7^{th} of July) and fall (1^{st} to 7^{th} of October). The design variables where the percentage of opacity of the variable opacity filter (i.e., α_{filter}), and the utility factor of the artificial lighting system (i.e., Fu) at each hour of sunlight and occupancy, respectively, of the weeks considered. The bounds of the design variables are: $0 \leq \alpha_{filter} \leq 1$ and $0 \leq Fu \leq 1$. The constraint was to have a minimum of 400 lux of light on workplane during working hours with combined artificial and natural lighting and the objective function to minimize was the energy consumption cost. The optimization procedure relies on Matlab “fmincon” tool.

Results of optimization have been compared with reference values for design variables, i.e.: a complete transparent state of the variable opacity filter and lights fully on during occupancy schedule. Fig. 4 compares the daily heat load of the optimized and unoptimized models for each season. Negative values of Q_{HVAC} represent cooling loads and positive values of Q_{HVAC} represent heating loads.

Fig. 4 clearly illustrates that optimizing the design variables (i.e., opacity) helps reducing the overall energy consumption as well as the cooling peak loads for each season of the year. We assumed a cost expressed by:

$$\mathrm{Cost}[\$] = \mathrm{EnergyCost}[\$/\mathrm{kWh}] \cdot (\mathrm{ArtificialLighting}[\mathrm{kWh}] + |Q_{HVAC}|[\mathrm{kWh}]) \quad (8)$$

where

$$\mathrm{QHVAC} = \frac{\mathrm{QHVAC}_{cooling}[\mathrm{kWh}]}{\mathrm{COP}_{cooling\_system}} \text{ when the system is in cooling mode}$$
$$\mathrm{QHVAC} = \mathrm{QHVAC}_{heating}[\mathrm{kWh}] \text{ when the system is in heating mode} \quad (9)$$

With an energy cost of 0.08$/kWh and a $COP_{cooling}=1$, we can evaluate the potential of energy consumption reduction and cooling peak loads for each season. Results are shown in Table 1.

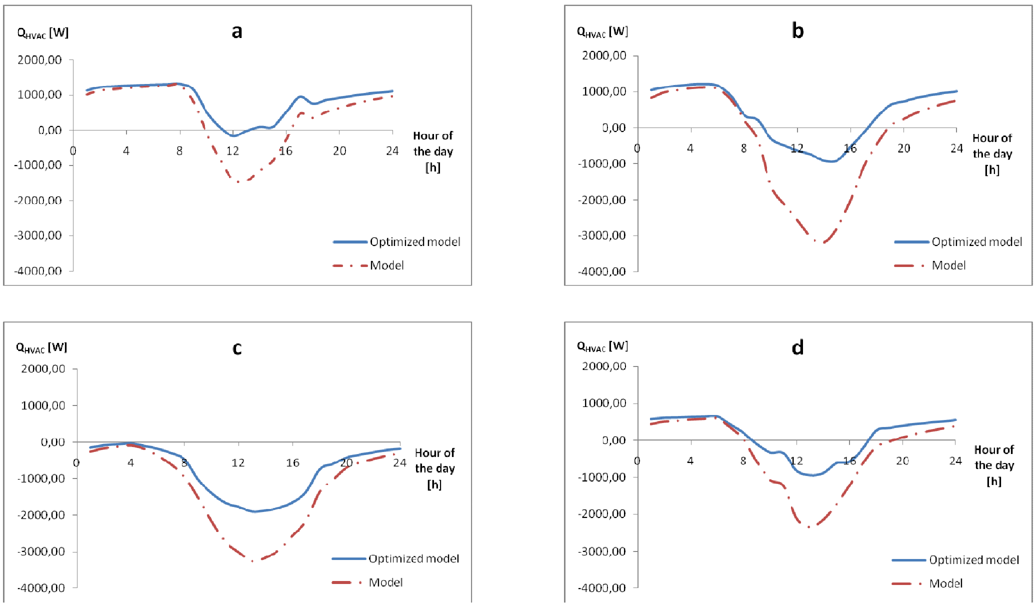

Fig. 4: Total mean daily sensible heat loads for the first week of: a) January, b) April, c) July, d) October.

With the help of Table 1, we see that results of energy savings are promising with at least 20% of savings during winter and a little more than 40% during other seasons. Since results have been obtained with data for only one particular week of each season, we cannot estimate precisely the yearly energy consumption. Still we can predict that the overall energy consumption reduction will be of the order of 35% by mean calculation for the type of building considered. Also, optimization results show an important reduction of cooling peak loads with a minimum reduction of 42%. This could be of great importance for energy consumers the electricity bill of which is based on peak consumption. Also, peak reduction allows to install smaller HVAC equipments which results in additional savings. Further works will evaluate more precisely these savings with a more sophisticated daylight model and an optimization of the design variables throughout the entire year.

Table 1: Energy saving and peak reduction results.

	Unoptimized results		Optimized results		Optimization improvement	
1st week of:	**Energy cost**	**Cooling Peak load [W]**	**Energy cost**	**Cooling Peak load [W]**	**Energy consumption reduction**	**Cooling Peak load reduction**
January	16,82 $	1435	13,26 $	160	21%	89%
April	18,79 $	3169	11,11 $	920	41%	71%
July	19,56 $	3255	11,17 $	1898	43%	42%
October	13,16 $	2323	7,77 $	912	41%	61%

CONCLUSION

In this paper, two models have been developed to evaluate the performance of smart windows (whose technologies are based on an absorbing layer) in order to reduce the overall yearly energy consumption of buildings. Results of the optimization of the design variables have shown that the integration of this glazing technology enhances considerably the buildings energy efficiency. It is shown that energy required for lighting, heating and cooling can be reduce up to around 20% during winter and more than 40% during warmer seasons.

This initial investigation is part of a larger research project aiming to predict the energy performance of new smart window technologies and to develop strategies of control to improve building yearly energy consumption. As mentioned previously, a sophisticated daylight model is being developed to improve natural light contribution. Furthermore, liquid crystal variable opacity filter prototypes will be characterized in order to give more precise optical properties to implement into the models.

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REFERENCES

1. A S Bahaj, P A B James and M F Jentsch, 'Potential of emerging glazing technologies for highly glazed buildings in hot arid climates', Energy and Buildings, Vol 40, No 5, pp 720-731, 2008.
2. J M Schultz and K I Jensen, 'Evacuated aerogel glazings', Vacuum, Vol 82, No 7, pp 723-729, 2008.
3. T T Chow, K F Fong, W He, Z Lin and A L S Chan, 'Performance evaluation of a PV ventilated window applying to office building of Hong Kong', Energy and Buildings, Vol 39, No 6, pp 643-650, 2007.
4. M N Assimakopoulos, A Tsangrassoulis, M Santamouris and G Guarracino, 'Comparing the energy performance of an electrochromic window under various control strategies', Building and Environment, Vol 42, No 8, pp 2829-2834, 2007.
5. D J Gardiner, S M Morris and H J Coles, 'High-efficiency multistable switchable glazing using smectic A liquid crystals', Solar Energy Materials & Solar Cells, Vol 93, No 3, 2009.
6. A Jonsson and A Roos, 'Evaluation of control strategies for different smart window combinations using computer simulations', Solar Energy, Vol 84, No 1, 2010.
7. B J Urban, 'The MIT Design Adivsor: Simple and rapid energy simulation of early-stage building designs', Massachusetts Institute of Technology, Department of Mechanical Engineering, pp 132, 2007
8. F C McQuiston, J D Parker and J D Spitler, 'Heating, Ventilating, and Air Conditioning Analysis and Design', Wiley, sixth Edition, pp 224, 2005
9. A De Rosa, V Ferraro, D Kaliakatsos and V Marinelli, 'Simplified correlations of global, direct and diffuse luminous efficacy on horizontal and vertical surfaces', Energy and Buildings, Vol 40, No 11, 2008.