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Solar Radiation Control Using Electrochromic Smart Windows, an Approach toward Building Energy Optimization

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Abstract

Due to notable part of buildings in the global energy consumption, it is of significant importance to design various scenarios to optimize building energy consumption. Smart windows including electrochromic types are some recently developed ideas that may help through this way controlling the solar radiation. Here a residential building is studied to analyze the performance of electrochromic smart windows in compare with simple single glazing and also triple glazing windows in the cities of Tehran and Yazd, as two choices of hot and dry climate. Results indicate that in the city of Tehran, when comparing with simple single glazing windows, in the case of use of electrochromic windows, 20% and 10% saving is observable in gas and electricity consumption, respectively. These are 17.1% and 7.2% when implementing triple glazing windows. In the city of Yazd also this trend has been experienced with 22% and 12.6% saving in natural gas and electricity in the case of electrochromic smart windows, respectively and that of 17.5% and 8.1% for triple glazing windows, respectively. So implementing this smart window type has led to the building energy optimization by the mean of controlling the amount of solar radiation allowed in the building.

Keywords: solar radiation, smart window, electrochromic, building energy optimization, climate.

Introduction

About one-third of the energy is wasted by windows in buildings so windows have a key role on energy consumption on building sector. Windows are also one of the weakest building components with high thermal losses. In the recent years, windows performance have been improved through different window and glazing technologies such as multi-layered glazing and the use of several types of coating, which in general make windows more energy efficient [1]. Traditional windows are normally a static building component, whereas the climate is in a continuous shifting state with changing temperatures and solar radiation. Hence, the trade-off between allowing positive solar heat gain, daylight and outside view, while preventing glare and overheating, is challenging. Accessory solar shading devices` such as blinds or curtains are often used; alternatively, advanced window technologies such as dynamic windows are under rapid development due to their abilities to change the optical properties in response to the climate or the user requirements[2].

Triple glazing units are becoming more and more widely used in modern buildings since they provide better performances of energy and thermal comfort by providing shading in summer and extra insulation in winter. It also protects the window from condensation on the external surface of the glazing [3]. Another factor that makes triple glazing superior is its thickness; thermal conductivity of the window drops as the windows layers increases[4] . Shakouri et al.[5] compared the thermal performance of double-glazed and triple-glazed windows. Different window sizes and orientations were taken into account in his study as well. The annual energy consumption for the double-glazed window was always higher than that of triple-glazed window, irrespective of orientations and window-to-floor ratios. This result highlighted the fact that double glazed fenestration systems allowed more gain in the solar heat compared to a triple-glazed window. Also, a triple-glazed system reduces the thermal transmittance of the windows, due to its additional insulation, making it more advanced in the context of thermal performance. Sadrzadehrafiei et al.[6] had also conducted an examination on triple-glazing and its benefits towards cooling energy in tropical climates such as Malaysia. The study compared the cooling energy savings that could be achieved by single clear glass and triple glazing. Moreover, the study also compared the performances of two triple-glazing with 15 mm and 16 mm air gap between them. Results of the study showed that triple-glazing was able to achieve cooling electricity savings of 6.3%, compared to a single clear glass. The savings by using a 16 mm air gap triple glazing is more than that in the 15 mm, but the difference was insignificant.

In comparison to traditional windows, smart windows are able to adjust the energy and light transmission values in relation to external environmental conditions and user's need. Despite of traditional windows, smart windows are compatible on climate conditions and it could change with temperature and solar radiation. The control of the incident solar radiation is a key element for the achievement of indoor wellbeing and more energy efficiency in buildings. Improving the design and manufacture of window systems seek to be optimized the effective use of solar resource, minimize undesired energy losses and effectively moderate the indoor environment[7]. Since the first applications in 2000's, relevant projects have demonstrated many advantages in the use of active dynamic glass, electrochromics in particular, such as savings up to 60% of the needs to artificial lighting, a reduction of the cooling load up to 20% and of peak power up to 26%, with the possibility of resorting to plants of smaller size [8-10]. Also studies indicate that the impact of electrochromic windows is highly dependent on climate. Other studies focused on energy consumption showed energy consumption decreases to 8-10% in temperate climates[11]. Also EC windows devices are able to control the solar radiation passage by varying the applied voltage, hence offering an elegant and dynamic to way to regulate the solar transmittance. Solar radiation at the earth's surface is located between 300nm where the visible radiation is between 380 nm and 780 nm. Solar radiation falling onto a material will be transmitted, absorbed and reflected and this amount of radiation is dependent the wavelength of the radiation, the incident angle and the optical and the optical properties of the material[12].

In winter solar heat harvesting can help reduce energy consumption for space heating and during summer excessive solar radiation passing through the glass can instead cause overheating of the indoor space resulting in high consumption for HVAC system.

EC materials belong to the category of property-changing smart materials and are able to autonomously and reversibly change their color due to oxidation or reduction reactions as a response to an external electrical stimulus. Some properties of EC windows are[13]:

- Visible Light Transmission about 60%-1%.
- Solar Heat Coefficient (Clear-Dark) about 0.46-0.06.
- UV transmission (Clear-Dark) about 0.4%-0%.
- No privacy in dark state.
- Typically 4 states light control levels from clear to dark.
- Continuous states between dark and clear.
- Operating temperature from -20 to 70C.
- They are typically blue or green.
- Operating voltage is 12V DC.
- Power requirement for state transition about 2.5 W/m2.

- Power requirement for state maintenance is 0.4 W/m2.
- Switching speed is typically 5-12 min and durability is about 30 years.

Electrochromism in thin films of metal oxides seems to have been discovered several times through independent work. Electrically induced color changes in thin films of tungsten oxide immersed in sulphuric acid were given a vivid description in an internal document at Blazers AG in Liechtenstein in 1953[14]. Ajaji and Andre [15]investigated the impact of electrochromic windows in an office building in Brussels. Energy simulations were conducted, and it was shown that primary energy consumption was reduced from 100.9 kWh/m^2 to 38.6 kWh/m^2 when controlling the windows by outdoor temperature and illuminance. The main cut in energy consumption was due to a lower cooling demand. Piccolo et al. [16]investigated the impact of electrochromic windows controlled by illuminance on a residential building compared to a reference window for two locations. It was found that the largest energy saving potential is in warmer climates and with a higher window-to-wall ratio due to a reduced cooling demand. Dussault and Gosselin [17]conducted a sensitivity analysis to address the relative effect of the main building design parameters on energy comfort improvements related to the use of smart windows. Energy simulations were performed for an office building for various combinations of the design parameters; location, façade orientation, window control, window to wall ratio, internal gains, thermal mass and envelope tightness. The conclusions are that the largest energy saving potential is due to a reduced cooling demand in warmer climates and higher solar radiation exposure. Szymon Firlag et al.[18] studied on controls algorithms for dynamic windows for residential buildings. The results show that: [1] use of automated shading with proposed control algorithms can reduce the site energy in the range of 11.6–13.0%; in regard to source (primary) energy in the range of 20.1–21.6%, [1]the differences between algorithms in regard to energy savings are not high, [2] the differences between algorithms in regard to number of hours of retracted shades are visible, [1] the control algorithms have a strong influence on shade operation and oscillation of shade can occur, [1] additional energy consumption caused by motor, sensors and a small microprocessor in the analyzed case is very small.

2. Materials and Methods

This study has two parts. The first part is focused on the analysis of the effects of using smart windows based on electrochromic windows on a residential building considered once located in Tehran and once in Yazd, in Iran. The second part of the study is about triple glazing windows in these two climates in Iran. Design Builder software is used to calculate the thermal loads in this case.

2.1. Case study

The studied model is a residential building located in Tehran and Yazd. The area of the building is about 800 m^2 and it has four floors. There is one unit on each floor with the occupancy of four people. The existing heating system uses100% natural gas and the existing cooling system use 100% electricity. At first step of calculations, the building considered with typical static single glazed window, clear, no shading and thickness of 6mm with PVC frame and no external shading. Then in next step of calculations, windows are replaced with electrochromic and triple glazing windows. All of the walls have thickness of 20 cm and the used insulation in external walls is cork. The reason for choosing this material for insulation is the efficiency of cork in thermal, sound and humidity resistance. Cork sheets can absorb 17% humidity without any deformation on its tissue and in comparison to gypsum is 10 times more resistance on sound transition. The occupancy on each unit is considered about four people. The comfort temperature is assumed to be 22 and 26 degrees of centigrade in winter and summer for residents. Figure 1 shows the plan of the building and figures 2 and 3 show the sun path diagram in different months of the year in Tehran and Yazd. Table 1 reports the site location information of Tehran and Yazd. Table 2 includes solar properties and U-values of electrochromic and triple glazing window types implemented in this work. Also figure 2 and figure 3 shows sun path diagram in Tehran and Yazd among year.

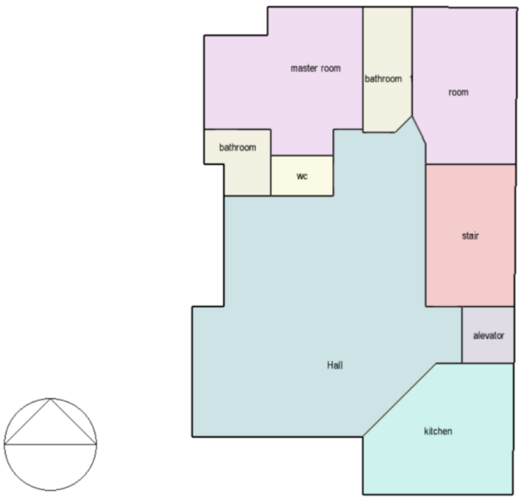

Figure 1. The plan of the building.

Table 1. Site location information of Tehran and Yazd. [19]

	Tehran	Yazd
Latitude (°)	35.68	31.9
Longitude (°)	51.32	54.28
ASHRAE climate zone	3B	2B
Elevation above sea level	1191	1237

Table 2. Window information. [19]

	Electrochromic	Triple glazing
Total solar transmission	0.638	0.675
Direct solar transmission	0.545	0.595
Light transmission	0.727	0.738
U-value	1.772	2.166

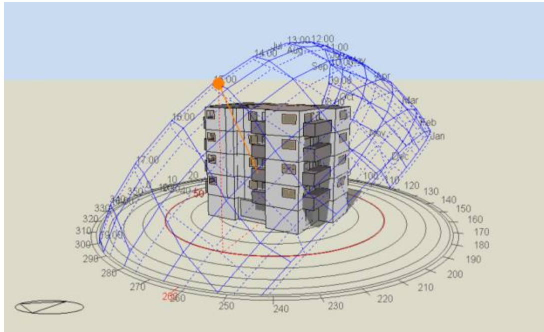

Figure 2. Sun path diagram of the building in Tehran.

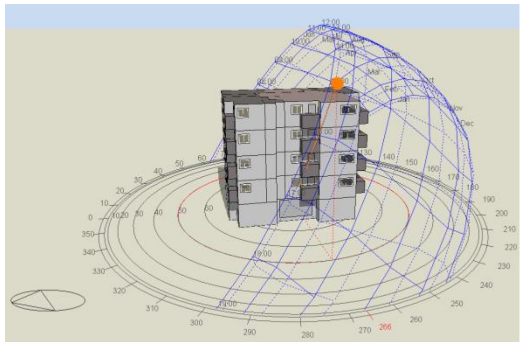

Figure 3. Sun path diagram of the building in Yazd.

2.1. Window's heat losses

The radiation from windows is very important parameter in cooling load calculations because always the direction of solar radiation on windows is from outside to inside the building. So in cold seasons it is useful and in hot seasons it is a disadvantage for HVC system. Cooling radiation load from windows can be calculated from equation 1[20]:

$$Q = \text{correction coefficient} * \text{storage coefficient} * \text{window's area} \; (ft^2) \qquad (1)$$

Q is the magnitude of the absorbed heat from sun and correction coefficient is depended on climate conditions. The storage coefficient indicates the part of thermal load that can be absorbed by the building. Thermal load losses from windows is also calculated from equation 2 [20]:

$$Q = U.A(T_o - T_i) \qquad (2)$$

In this case the amount of U is considered about 1.13 for typical window.

Another important factor for heating and cooling loads is Solar Heat Gain (SHG) from windows and external glasses and is calculated from equation 3 [21]:

$$Q = SHG \times A \times k_1 \times k_2 \times k_3 \times k_4 \times k_5 \times k_6 \quad (3)$$

In equation 3, Q indicates cooling load originated from solar radiation on windows' glass, k_1 is correction coefficient and depends on the glass type and colour of the internal or external shading and in this case it is considered for a typical no coloured glass and the amount of this is 0.9. k_2 is storage coefficient, k_3 is frame coefficient if the frame is metal the coefficient would be 1.175, k_4 is height coefficient and depended on sea level and is calculated from equation 4:

$$k_4 = [1 + 0.007 [1 + 0.007 \times \frac{H}{1000}]] \quad (4)$$

k_5 is dew point coefficient and is found from equation 5 :

$$k_5 = [1 \pm 0.07 \times \frac{66.8 - D.P.T}{10}] \quad (5)$$

k_6 is the coefficient of cleanness and depends on the magnitude of dust and fog in the ambient air. In a very clean air it is equal 1.15. In a normal air that is neither very dusty nor very clean, this coefficient is 1 and in a dirty condition it is 0.85. In the current study the coefficient of cleanness is considered 1 as a normal situation.

3. Results & Discussion

Design Builder software was used in this study to calculate cooling and heating loads of the building in different design condition. At first calculation of thermal loads was done with typical single glazing window without any shading. Heating system of the building used 100% natural gas in the cold months and cooling system used 100% electricity in the hot months.

The effect of implementing smart electrochromic windows on energy consumption of the building (both electricity and natural gas) has been studied. Figures 4 and 5 reports the results of sensible heating and sensible cooling of the building in the case of Tehran for all tree studied systems during different months, respectively.

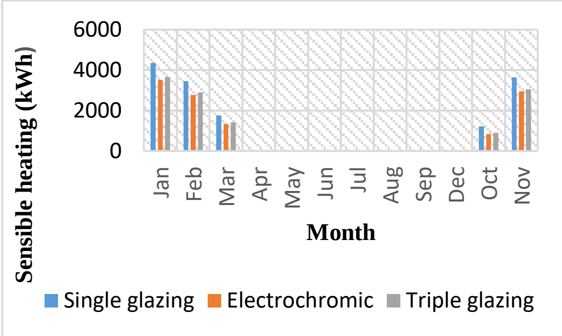

Figure 4. Sensible heating of the building in Tehran.

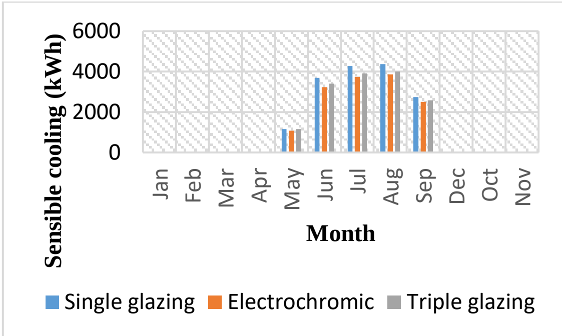

Figure 5. Sensible cooling of the building in Tehran.

It is observable that in all over the year, both of sensible heating and cooling loads of the building experience their minimum when the electrochromic windows have been implemented. The second place belongs to triple glazing type of windows here.

Figure 6 reports the heating loads that are supported with natural gas for the building in all of the studied cases when it is located in Tehran city. Figure 7 shows the cooling loads that are deled using electricity.

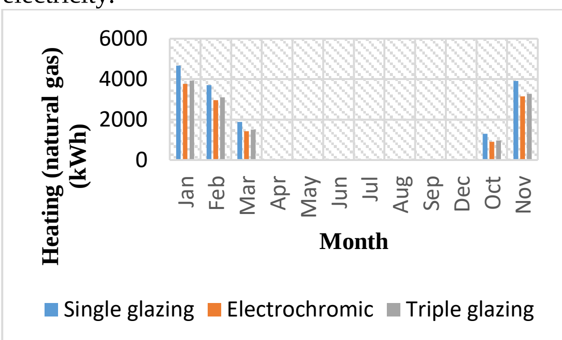

Figure 6. Heating from natural gas in Tehran.

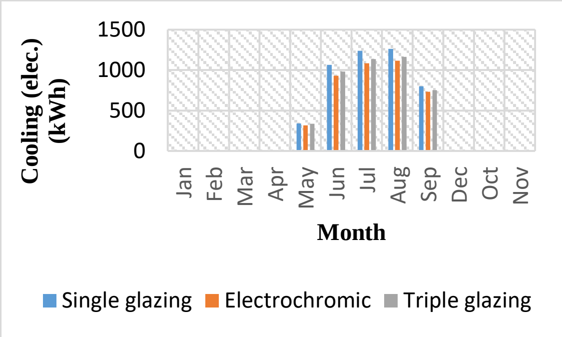

Figure 7. Cooling supported by electricity in Tehran.

It is understood that implementing electrochromic windows has led to the minimum energy consumption in both of natural gas for heating and electricity for cooling in Tehran. Table 3 reports total yearly energy consumption of the building in city of Tehran for both category of natural gas and electricity.

Results indicate that when comparing with simple single glazing windows, in the case of use of electrochromic windows, a 20% and 10% saving is observable in gas and electricity consumption, respectively. These are 17.1% and 7.2% when implementing triple glazing windows.
Figures 8 and 9 show the sensible heating and cooling of the building when considered in Yazd city, respectively.

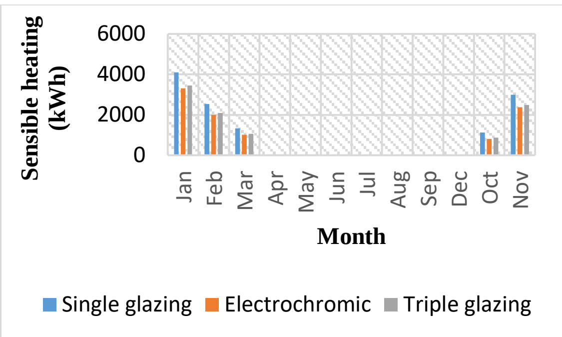

Figure 8. Sensible heating of the building in Yazd.

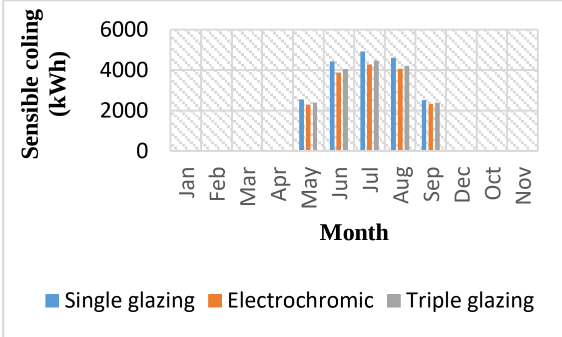

Figure 9. Sensible cooling of the building in Yazd.

Results show that in all of the months, both of sensible heating and cooling loads of the building have their minimum when the electrochromic windows have been implemented. Figures 10 and 11 indicate the heating loads supported by natural gas and the cooling ones supported by electricity for experience of Yazd city, respectively.

Table 3. Total yearly energy consumption (both natural gas and electricity) in Tehran.

Window type	Total heating (Gas) (kWh)	Total cooling (Electricity) (kWh)
Single glazing	15448	4707
Electrochromic	12208	4180
Triple glazing	12761	4368

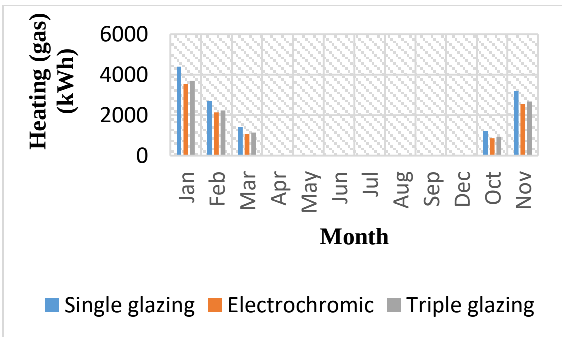

Figure 10. Heating supported by natural gas in Yazd.

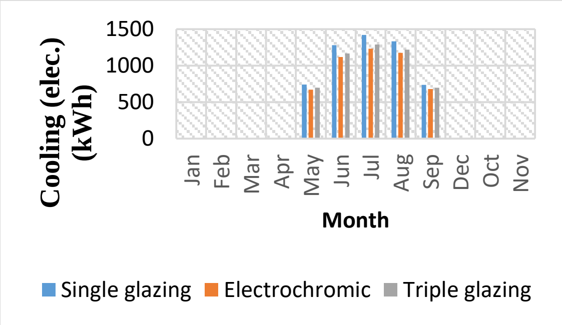

Figure 11. Cooling supported by electricity in Yazd.

The fact that the electrochromic windows act powerfully as an energy saver and are good tools to achieve an energy optimized building, is obvious here again for the building when located in the city of Yazd. The total yearly energy consumption of the building is reported in table 4 in this case.

Table 4. Total yearly energy consumption in Yazd.

Window type	Total heating (Gas) (kWh)	Total cooling (Electricity) (kWh)
Single glazing	12946	5512
Electrochromic	10162	4872
Triple glazing	10677	5063

Results indicate that when comparing with simple single glazing windows, in the case of use of electrochromic windows, a 22% and 12.6% saving is observable in gas and electricity consumption, respectively. These are 17.5% and 8.1% when implementing triple glazing windows. It is noticeable that in the city of Yazd the performance of the smart electrochromic windows is better in compare with that of the city of Tehran.

4. Conclusions

In this research, a residential building was analyzed to find the performance of electrochromic smart windows in compare with simple single glazing and also triple glazing windows. The study was run in the two cities of Tehran and Yazd with ASHRAE climate zones of 3B and 2B, respectively. Results showed that in the city of Tehran, when comparing with simple single glazing windows, in the case of use of electrochromic windows, 20% and 10% saving was achieved in gas and electricity consumption, respectively. These are 17.1% and 7.2% when implementing triple glazing windows. In the city of Yazd also this trend was reported with 22% and 12.6% energy saving in natural gas and electricity when implementing the electrochromic smart windows, respectively and that of 17.5% and 8.1% for triple glazing windows. It is concluded that this smart window type leads to the building energy optimization by the mean of controlling the amount of solar radiation allowed in the building. It is proposed to study the performance of photochromic type windows and compare the results in future studies.

Acknowledgements

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Nomenclature

Q	Thermal radiation load from windows
A	area of window (ft^2)
U	Heat transfer coefficient (B.T.U /(hr.ft².F))
T_i	Indoor temperature (F)
T_o	Outdoor temperature (F)
SHG	Solar Heat Gain
k_1	Correction coefficient
k_2	Storage coefficient
k_3	Frame coefficient
k_4	Height coefficient
k_5	Dew point coefficient
k_6	Coefficient of cleanness
H	Height above sea level
D.P.T	Dew point temperature (F)

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