ADVANCED CONTROL OF ELECTROCHROMIC WINDOWS

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ABSTRACT

In our research we use the technology of electrochromic (EC) glazing to maximize the use of daylight and minimize the energy consumption in buildings while preserving visual and thermal comfort of the users. We propose an advanced automatic control of EC windows coupled with an anidolic daylighting system (ADS), blinds and dimmable fluorescent lights. EC windows with a visible transmittance range (Tv) of 0.15 – 0.50 were installed on the southern façade of an office room of the LESO experimental building (EPFL campus in Lausanne, Switzerland). The system is divided in two independent zones: The lower zone is equipped with EC windows and blinds while the upper zone features in addition the ADS, which facilitates the even distribution of daylight across the room. Electric lighting is used only complementary when daylight is not sufficient. Data regarding instantaneous weather conditions, room conditions, as well as user wishes is collected and recorded in the database of the building's central management system (KNX/EIB).

To address visual comfort requirements, a novel sky-scanner approach is implemented into a predictive control strategy to take into account the time the EC glazing requires to switch between different transmission states (up to 15 minutes). For the thermal comfort, we consider a wider time horizon, taking under consideration also the time, day and season. User has always the possibility of manually overriding the automatic control system. Adaptive fuzzy logic algorithms are implemented allowing the system to learn from users' wishes. Simulations showed that the elaborated algorithms for the automatic control of EC windows can provide better thermal and visual comfort conditions when compared to standard glazing coupled with blinds and still exhibit acceptable levels of energy consumption for space heating and electric lighting. Field study results showed that workplane illuminances were mostly kept inside acceptable visual comfort levels (at around 450-1000 lx). Field survey results regarding the acceptance of the system by the users are also presented along with a discussion on the efficacy of an EC windows system to handle glare issues without the use of blinds.

Keywords: electrochromic windows, advanced automatic control, building energy saving, visual and thermal comfort, adaptive and predictive control algorithms, user acceptance

1. INTRODUCTION

The concept of harvesting and using daylight in buildings reflects positively on all three pillars of sustainability: it has a significant energy saving potential; it reduces energy-related costs and it has positive effects on the well-being of building users. Electrochromic (EC) glazing has been commercially available the last few years as an alternative to the combination of standard window glazings with mobile solar shadings (very often discarded by the architects) or to permanently tinted solar protection glazings. EC glazing has the ability of changing dynamically its optical properties and modulating the transmission of visible light and heat solar gains through the window, while maintaining at all times the view towards outside. Several research studies have been carried out during the last few years with regard to the use of EC windows in buildings [1; 2; 3]. In some of these, the visual or thermal comfort is evaluated through computer simulations or with the use of small-scale models. While this type of research involves an easier setup, is favourable for the study of energy aspects and allows for the execution of different scenarios, it lacks the evaluation of visual or thermal comfort by real persons in real-life situations. In this study we experiment on a full-scale model.

Also, studies carried out until now have essentially considered a manual control of the EC glazing transmission. Some rather elementary automatic control strategies have been investigated, such as the closed loop control based on the measurement of the inside daylighting contribution. Nevertheless, the time characteristics of EC glazing (delayed response of the transmission variation after a command, usually between 5 and 15 minutes) have not been taken into account in these elementary automatic control strategies. In this direction, we developed an optimized control algorithm (which takes account both the energy and the visual comfort aspects), with an innovative short term prediction of incident solar radiation based on a sky-scanner approach and including the user's preferences.

The presented results include an experimental check of the control system on an office room of the LESO Building. This room is equipped completely with EC glazing, both for the lower window and the anidolic daylighting system (ADS). The experimental check has been carried out with real persons, allowing therefore the evaluation of the system by the users. Results of extensive simulations are also presented herein. In these, different control scenarios were tested against a long period of time (one year) and against varying meteorological conditions. The simulations allowed for the comparison of the energy consumption for heating and electric lighting as well as for an estimation of thermal and visual comfort of each case.

2. METHOD

Control algorithm

The developed control algorithm predicts an optimal setting for the EC glazing, the blinds and electric lighting taking into account all the available data on instantaneous weather condition and building state, including data on room occupancy and user wishes/actions, workplane illuminance, internal air temperature. The algorithm predicts this optimal setting at a time horizon corresponding to the EC glazing latency time (5 to 15 minutes). Electric lighting is commissioned only complementary when daylight is not sufficient, while blinds are likewise only employed to protect from glare and/or to avoid overheating when protection from EC windows is not sufficient. A longer time horizon is taken into account for the thermal aspects. Moreover, when the room is occupied priority is given to visual comfort, while if the user is absent the algorithm is optimized for thermal comfort.

To tackle with the issue of the slow switching speed of the EC windows we implemented a predictive algorithm based on image processing of sky images taken by a standard web camera. The camera is placed below the skylight of an office room where it has an almost unobstructed view of the sky. It faces towards the south at a measured angle 'z' from the zenith, making sure the sun trajectory is included in the images taken. A fish-eye lens, capturing the whole sky dome is important and maximizes the prediction window. In this project, no wide angle lens has been used; therefore the prediction window stays at about 5 min. The camera was setup to take automatically images of the sky at fixed time intervals. It was observed that for low or moderate wind speeds the time interval of 1 min is sufficient for the observation of changes in the sky concerning the motion of clouds. However, higher wind speeds require a shorter time interval. The images taken with the camera are stored in the PC and processed in a way that (1) the relative motion of clouds between 2 consecutive images is detected; (2) analysis of the cloud motion using a series of images is performed; (3) the possibility of clouds to obscure the sun during the next 5 minutes is deducted and passed on to the fuzzy control system [4; 5] so it can issue on time the appropriate commands to the EC windows, blinds and electric lighting.

Simulations

The parametric study allowed for the testing of different control scenarios over a long period of time (one year) and against varying meteorological conditions. Energy consumption for heating and electric lighting as well as estimation of thermal and visual comfort was the output. Simulations were performed using dynamic thermal simulations code that has been developed by LESO laboratory. The code was modified and expanded to include the EC glazing characteristics, the developed control algorithm, electrical lighting features (modules for the calculation of illuminance levels on desktop and energy consumption) and visual and thermal comfort prediction modules. The model used in all simulations was a simplified 13-node model of a South-facing office room similar to the LESO building room where the EC glazing was installed. North, West and East are partition walls adjacent to other offices and the corridor. Ceiling and roof are also adjacent to other offices. The blinds considered are made of textile tissue and they can roll up (completely open) and down (when closed). For the electric light use, the visual and the thermal comfort we consider the presence of a user only during the working hours with a 9-hour daily schedule of 08.00 to 18.00 with a lunch break from 12.00 to 13.00, from Monday to Friday. Window surface was modeled as a single window instead of the coupling of a window with ADS.

The following scenarios of windows of a South-facing office room were compared:
1. Conventional transparent double glazing;
2. Conventional transparent double glazing coupled with blinds and a simple control strategy, depending only on incident solar radiation and season;
3. Solar protection glazing with SHGC=0.38 and Tv=0.50;
4. Solar protection glazing with SHGC=0.12 and Tv=0.15;
5. EC glazing with simple control scheme (same as on 2.);
6. EC glazing with the proposed control algorithm;

Thermal comfort

To calculate thermal comfort, we compare the indoor temperature across the different simulation scenarios. We then analyse thermal comfort using Fanger’s model [6]. Using as input for every time step of the simulation the season, the radiant temperature in the room and the room’s air temperature, the Predicted Percentages of Dissatisfied (PPD) were generated for every working hour in the year.

Visual comfort estimation

To estimate the visual comfort we build upon the work of Lindeloef regarding the Bayesian optimization of visual comfort [7]. Lindeloef calculates the user’s Visual Discomfort Probability (VisDP) as a function of the horizontal workplane illuminance only (no illuminance data was used). Based on his work, we establish the illuminance limits for the VisDP and we evaluate the ability of the simulated case studies to keep the workplane illuminance levels within the ranges which are less likely to cause discomfort to the occupants.

Field measurements and user evaluation

Field tests of the algorithm were not extensive but they allowed for a short check of the elaborated algorithm on the experimental level. Short satisfaction surveys were conducted with 9 persons who volunteered to spend time inside the office room were the EC glazings are installed. Subjects spent roughly 2 hours in the room (under similar weather conditions for all the persons). They spanned all age groups, both genders (2 female and 7 male) and spent their time doing ordinary desk work (mainly reading from paper, and computer work) facing all possible directions inside the office room (windows, side and back walls).

3. RESULTS

Energy consumption

The results of the simulation study regarding the energy consumption for heating and electric lighting are shown on Figure 1. As expected, standard (clear) glazing permits high solar gains during the winter which results in significantly low energy demand for space heating. In these cases, energy required for electric lighting is also reduced when compared to other cases due to the abundant daylight entering the room (note that LESO building allows important solar gains if no shading is used). However, both cases of standard glazing offer the worst visual and thermal comfort (overheating and extreme illuminance) as seen next.

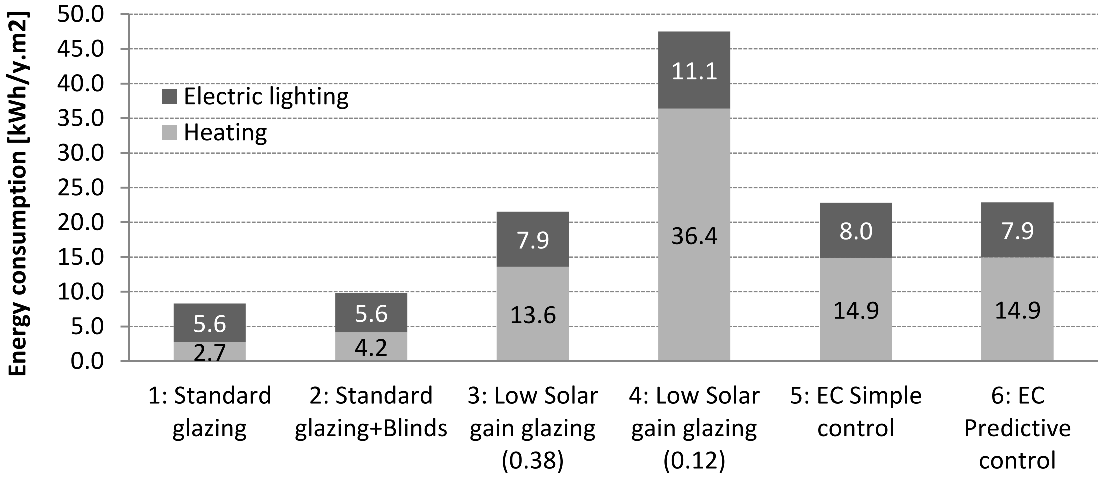

Figure 1: Annual energy demand for space heating and electric lighting for different simulation scenarios

Scenario 4 appears on the other extreme in terms of energy demand. This case features a low solar gain glazing with a very low constant coefficient of solar radiation transmission of 0.12. Solar gains are mostly cut-off and energy demand for heating escalates to over the double in comparison to the other scenarios. Energy demand for electric lighting is also significantly higher (about 40%) when compared to scenarios 3, 5 and 6. This is due to the constant low visible light transmission and the subsequent more frequent use of electric lighting.

The energy demand of the case of low solar gain glazing with a constant coefficient of solar radiation transmission of 0.38 (scenario 3) is comparable to the energy demand by the scenarios 5 and 6 with the EC glazings. It is thus important to compare these 3 scenarios in respect to the predicted visual and thermal comfort they offer.

Thermal comfort

The comparison between all different scenarios (Figure 2) shows clearly that automatically controlled EC windows (scenario 5 and 6) provide the best possible thermal comfort conditions with only a 15.6% of working time during the winter season found outside the thermal comfort limits. Scenario 3 also provides acceptable thermal comfort with 21% of working time during the winter season lying outside the thermal comfort limits. Standard glazing scenarios provide unacceptably high discomfort conditions. During winter, scenario 4 interestingly enough provides the “perfect” thermal comfort conditions with zero working time being outside comfort conditions. That is of course due to the excessive use of heating energy since almost all solar gains are rejected (See *Energy consumption* above). *Please note that the abnormally elevated discomfort percentages during the heating season are mainly due to the absence of any cooling strategy (even passive).*

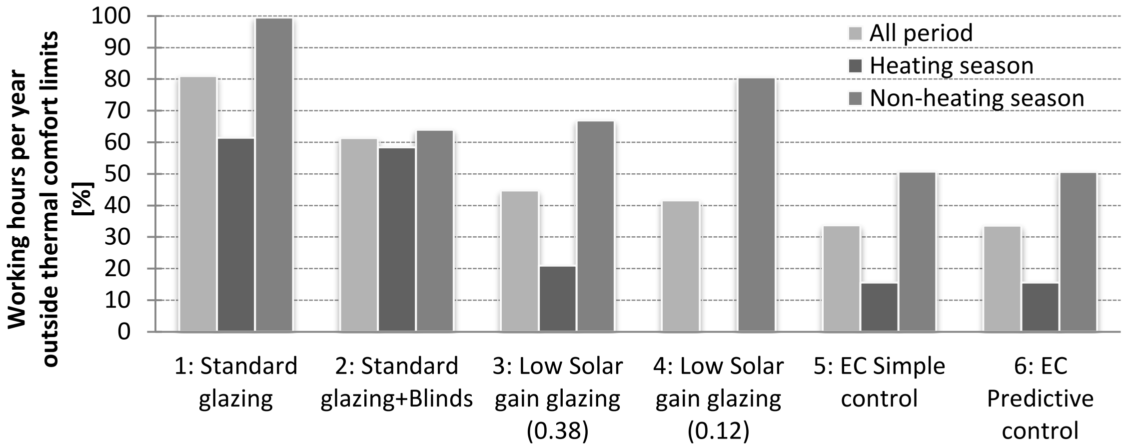

Figure 2: Percentage of working time during the simulation period where temperature is outside comfort limits and the PPD is over 10%, for each of the six considered simulation cases.

Visual comfort

Extreme-case scenario 4 demonstrated the best possible visual performance between the studied cases, followed closely by the EC windows scenarios (5 and 6) and scenario 3, although that is true only for the illuminance ranges corresponding to discomfort probability below 0.35. Scenarios 5 and 6 appear to achieve same levels of visual comfort in this analysis. Nevertheless, a comparison of the 2 scenarios against the same weather conditions and time period, shows that predictive control strategy (scenario 6) maintains workplane illuminance more stable compared to simple control (scenario 5). Workplane illuminance in non-predictive control tends to fluctuate in unison with external irradiance levels.

Field testing and user evaluation

Measured workplane illuminances were kept inside acceptable visual comfort levels (at around 450-1000 lx) most of the time during a day with intermediate sky conditions. Concerning user evaluation, most users were not satisfied by the unnatural colour rendering of the room and/or that of the view when looking outside, especially when the windows were fully tinted (Persian blue colour). Glare issues were also mentioned by half of the persons, which eventually motivated them to use the blinds. This was true in cases that direct sunlight hit the desk and/or the computer monitor. Also, some users expressed the wish for a wider dynamic range of possible transmissions (on both ends). However, most users are willing to oversee any inconveniences or disadvantages of EC windows and they are generally positive when comparing this daylighting system to a standard one (i.e. blinds) mainly due to the unobstructed view that EC windows offer at all times. Users did not express dissatisfaction regarding the control of the EC Windows nor did they seem to consider negatively the slow switching time between different transmission levels.

4. DISCUSSION AND OUTLOOK

Simulations showed that the elaborated algorithms for the automatic control of EC windows can provide better thermal and visual comfort conditions when compared to standard glazing coupled with blinds and still exhibit acceptable levels of energy consumption for space heating and electric lighting. Permanently tinted windows (solar protection windows) with a SHGC=0.38 (the same as the clear state of EC windows) can offer competitive conditions as EC windows, exhibiting slightly worse thermal and visual behaviour, especially during days when solar gains are high (sunny days), which is expected since they cannot modify their transmission and block unwanted solar radiation. Field study results showed that workplane illuminances were mostly kept inside acceptable visual comfort levels, while the user acceptance of the daylight control system is severely impaired by the unnatural colour rendering of the room and of the view when looking outside. As it was expected, glare issues were mentioned by some users and blinds were employed in these occasions. However, most users seem to prefer EC windows to a standard daylight control system such as blinds, mainly due to the unobstructed view that EC windows offer at all times.

As it became evident during the comprehensive parametric study, the developed sky prediction algorithm does not outperform a simpler closed-loop algorithm based on external irradiation when considering energy consumption aspects. In respect to visual comfort, the two control systems perform similarly when analysed for the Visual Discomfort Probability (VisDP). However, under varying intermediate sky conditions predictive control strategy minimizes workplane illuminance fluctuation when compared to simple control and thus, it provides a more stable luminous working environment.

As a further step, we aim to implement extensive field experimentation and an in-depth user survey in order to validate our results.

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REFERENCES

1. Lee, E.S., et al. Advancement of Electrochromic Windows. *Lawrence Berkeley National Laboratory.* 2006. LBNL-59821.

2. Baetens, R., Jelle, B.P. and Gustavsen, A. Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. *Solar Energy Materials and Solar Cells.* 2010, Vol. 94, 2, pp. 87-105.

3. Lee, E.S. and DiBartolomeo, D.L. Application issues for large-area electrochromic windows in commercial buildings. *Solar Energy Materials and Solar Cells.* 2002, Vol. 71, 4, pp. 465-491.

4. Guillemin, A. *Using genetic algorithms to take into account user wishes in an advanced building control system.* PhD thesis no. 2778, EPFL. 2003.

5. Morel, N., et al. Neurobat, a predictive and adaptive heating control system using artificial neural networks. *International journal of sustainable energy.* 2001, Vol. 21, 2, pp. 161-201.

6. Lindeloef, D. *Bayesian optimization of visual comfort.* PhD thesis no. 3918, EPFL. 2007.

7. Fanger, P.O. *Thermal comfort analysis and applications in environmental engineering.* New York : McGraw-Hill, 1970.