Optimal Control of Electrochromic Windows for Minimum Energy Use in Commercial Buildings

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ABSTRACT

Detailed studies of control strategies for switchable electrochromic windows have been performed using the GSL Glazing Selector program in order to determine the optimal control strategy for these windows to minimise energy performance in commercial buildings in Australian climates. The results show that, not surprisingly, there is a strong orientation and climate dependence in both the type of parameters which should be used to control the switching of the windows, and also that the values of these parameters are sensitive to orientation and climate. The principal parameters which are important are the external temperature and the normal irradiance on the window. However, the results also depend strongly on the daylighting model used, and the flexibility in the lighting system in the building, as the principal benefits arise from the trade off between increased cooling energy and reduced lighting energy.

NOMENCLATURE

$I_n$ - normal irradiance on a window (direct + diffuse) (W/m²)
$T_{ext}$ - external temperature, (°C)
$T_{int}$ - internal building temperature, (°C)
$T_{glass}$ - glazing temperature in a building, (°C)
$\tau_{int}$ - interior time constant of a building, representing thermal energy storage in the building, (hours)
t - time of day (in hours)
L - effective daylighting power in a room
$T_{sol}$ - solar transmittance; ie transmittance weighted by the energy in the solar spectrum (%)
$T_{vis}$ - visible transmittance; ie transmittance weighted by the response of the human eye (%)

INTRODUCTION

The use of switchable electrochromic windows (Bell and Matthews (1998)) poses a question about how to control the devices to achieve maximum energy savings. There have been numerous studies which show that significant energy savings can be achieved in a range of climates (Sullivan et al, (1995), Macrelli et al (1996), Bell et al (1995)). It is generally agreed (Sullivan, et al 1995; Bell et al, 1996) that energy savings are greater for commercial buildings than for domestic houses, and the cost of electrochromic glazings will probably also limit their initial use to commercial buildings. Since the energy use of commercial buildings in Australia is increasing by 4.4% per annum, and cooling and lighting currently account for 21% and 15% of energy use (and 28% and 21% of greenhouse gas
emissions respectively) in commercial buildings (EMET Consultants and Solarch, (1999)), it is imperative for Australia's future to look to all possible technological solutions which can cost effectively reduce these components of commercial building energy use.

However, there are numerous outstanding questions about the real benefits to be obtained from switchable glazings on all faces of a building, in particular whether it is suitable to use a single control paradigm on different faces of a building, or in different climates. One of the difficulties in answering these questions lies in the paucity of modelling programs which allow for switchable glazings, and which provide sufficient alternatives to control of the windows. DOE2.1 (Sullivan, 1995) can accommodate electrochromic switchable glazings, and several other packages have been adapted to allow switchable glazings. However, these are also quite complex to run, and do not necessarily allow sufficient flexibility to assess the full range of possibilities. The GSL glazing selector (Moore, Bell and Willwrath (1998)), developed by the Australian Cooperative Research Centre for Renewable Energy, incorporates several control paradigms for variable transmittance glazings, and has been used in this work to explore a wide range of parameters to determine the effects of switching windows on building energy use, and in particular, how the various components of energy use are affected by different switching control parameters.

This study is not an in-depth analysis of the benefits which potentially can be obtained, as it is restricted to a simple set of building parameters, covering an air-conditioned (temperature regulated) office type module in a commercial building. It is designed to explore the changing requirements of switching parameters across climate and location in Australia. The conclusions show that while it may be possible to develop a generic switching strategy, the details of lighting energy distribution are crucial, and that for optimum performance the must be well understood and accurately modelled.

**GSL IMPLEMENTATION OF SWITCHABLES**

There are numerous different environmental parameters which could be used to control the switching of an electrochromic glazing. These are summarised in Table 1 below, which also indicates whether this parameter has been incorporated into the GSL program. The key element of the implementation of switching of a glazing between two different transmittance states is that in most cases, apart from external temperature or solar irradiance, the decision on whether to switch the window can only be made after simulations have been performed, which may then necessitate a second simulation to obtain the energy performance of the building. The method for setting these parameters within GSL is illustrated in Fig. 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Implemented</th>
<th>Method*</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Temperature $T_{ext}$</td>
<td>Yes</td>
<td>If($T_{ext} &gt; T_{ext, set}$) allow switching</td>
<td></td>
</tr>
<tr>
<td>Internal Temperature $T_{int}$</td>
<td>Yes</td>
<td>If($T_{int} &gt; T_{int, set}$) allow switching</td>
<td>Not assessed in this work ($T_{int}$ is controlled). Requires dual simulation</td>
</tr>
<tr>
<td>External irradiance $I_{e}$</td>
<td>Yes</td>
<td>If($I_{e} &gt; I_{e, set}$) allow switching</td>
<td>$I_{e}$ includes direct &amp; diffuse radiation normally incident on window</td>
</tr>
<tr>
<td>Glazing Temperature $T_{glass}$</td>
<td>Yes</td>
<td>If($T_{glass} &gt; T_{glass, set}$) allow switching</td>
<td>Requires dual simulation</td>
</tr>
<tr>
<td>Interior Daylight Illuminance $L_{int}$</td>
<td>No</td>
<td>N/A</td>
<td>Requires improved method of estimating interior daylight illuminance.</td>
</tr>
<tr>
<td>Time of day, $t$</td>
<td>Yes</td>
<td>if($t_{on} &lt; t &lt; t_{off}$) allow switching</td>
<td></td>
</tr>
</tbody>
</table>

* the parameters $T_{ext, set}$, $T_{int, set}$, $I_{set}$, $T_{glass, set}$, $I_{on}$ and $I_{off}$ are all controllable within GSL (see fig. 1).

**Table 1:** The control parameters which could be used for switchable windows.
Within the current version of GSL, the illuminance and all temperatures conditions are combined using an "OR" logical test, so that any one parameter can trigger the switching of the glazing. The time condition overrides this, resulting in the following logical structure:

\[
\text{If} \left( (T_{\text{ext}} > T_{\text{ext, set}}) \text{ OR } (T_{\text{int}} > T_{\text{int, set}}) \text{ OR } (I_{\text{n}} > I_{\text{n, set}}) \text{ OR } (T_{\text{glass}} > T_{\text{glass, set}})) \right)
\text{ AND } (t_{\text{on}} < t < t_{\text{off}}) \text{ then switch window to dark state}
\]

\[
\text{If} \left( (T_{\text{ext}} < T_{\text{ext, set}}) \text{ AND } (T_{\text{int}} < T_{\text{int, set}}) \text{ AND } (I_{\text{n}} < I_{\text{n, set}}) \text{ AND } (T_{\text{glass}} < T_{\text{glass, set}})) \text{ OR } ((t < t_{\text{on}}) \text{ OR } (t > t_{\text{off}})) \text{ then switch window back to transparent state}
\]

Figure 1: The switching tab in GSL, showing the controls used to set the switching of the window.

The inclusion of glass temperature is significant in that this allows the modelling of thermotropic and thermochromic glazing (Bell and Matthews, 1998) within GSL. This is quite difficult in most simulation programs as calculation of the glazing temperature requires a complete heat balance to be performed, and therefore involves two simulations in general. Note that in a double glazed unit, the temperature is the outer pane temperature.

As an example of the effect of switching a window, the direct solar radiation transmitted through a north facing window in Brisbane for June 5 (1986 TRY year data) is shown in Figure 2 for each hour of the day for three different switching settings: no switching; \(I_n > 200 \text{ W/m}^2\) and \(I_n > 400 \text{ W/m}^2\). The effect of switching the window on the transmitted energy is clear, with a significant reduction in the intensity of solar radiation entering the building (9.4kWhr for no switching vs approx 3kWhr for either switching option). Also, for this case (location, orientation), the relatively small effect of the different normal solar intensity is also clear, with the only difference between the two conditions being at 8am.
Figure 2. The direct solar radiation power entering the modelled building (see below) for three values of the normal irradiance. Results are for a north facing window in Brisbane with a glazed area of 9.7 m$^2$, and a solar transmittance of 47\% (clear state) and 14\% (coloured state).

**BUILDING MODELED**

All the modelling has been carried out on an office module 4m wide x 6m deep and with a 3m ceiling height. The office module is assumed to be embedded in a large (> 3 storey) office building of concrete or similar construction, so that side walls, ceiling and floors are adiabatic, but with some heat transfer allowed with the core of the building (rear wall U-value of 0.65 W/m$^2$). The exterior wall is insulated with a U-value of 0.65 W/m$^2$. There are internal loads in the building of 16 W/m$^2$, lighting is set at 12 W/m$^2$ with dimmable lights operating from 7am to 8pm. The building is assumed to be conditioned to remain within 22-25$^\circ$C, with the heating and cooling system operating from 7am to 7pm.

Several thousand simulations were performed across a range of values of the external temperature and normal solar illuminance on the window, and for all four cardinal orientations in Sydney, Melbourne, Brisbane and Perth. A base case simulation was also conducted in each location using an Azurelite-Sungate 100 laminate ($T_{sol}=36\%$; $T_{vis}=66\%$). The switchable electrochromic glazing used is based on devices made by Sustainable Technologies Australia, has $T_{sol}=47\%$ and $T_{vis}=62\%$ in the clear state and $T_{sol}=14\%$ and $T_{vis}=23\%$ in the coloured state. All glazings were used in double glazed units with a clear inner pane. A set of simulations to establish how sensitive the switching conditions and energy performance are to selection of the building parameters, and in particular the thermal mass of the building, was also run to determine the range of applicability of these results.

**RESULTS**

Several sets of simulations were performed to investigate the effect of different parameters of the building and its operation on the performance. This was primarily to determine the range of applicability of the conclusions which are drawn from the analysis of optimum switching strategies, i.e. the values of the switching parameters (see Table 1) which give the minimum energy requirement for the building. Note that because the building modelled is conditioned, the principal conditions which can vary are $I_n$ and $T_{ext}$ and this study concentratres on these parameters. The effect of switching of the windows is shown in Figure 3 for a wide range of window-wall ratios (WWR) and for all orientations of a building. The results are similar over all orientations, with differences principally in the magnitude of the energy consumption and energy savings. The largest energy savings occur for the largest windows for all orientations, which is a consequence of increased lighting energy savings for larger windows, which counteract the larger cooling loads for larger windows. Figure 4 shows the energy consumption for a north facing window for a wide range of building thermal masses, measured.
using the $\tau_{\text{interior}}$ time constant in GSL. The results are very consistent for different thermal mass buildings, so all results in this paper are for $\tau_{\text{interior}}=18$ hours. Results are also shown for the use of an Azurelite+Sungate100 laminate double glazed unit, and this shows that the switchable nature of electrochromic glazings saves energy over existing advanced, but non-switchable, glazings.

**Figure 3:** Annual Energy Consumption for the modelled office in Brisbane as a function of window-wall ratio. Solid lines are for cases where the windows switch optimally, and dashed curves are for non-switching windows. ▲ - north; ▼ - south; ■ - west; ● - east.

**Figure 4:** Annual Energy for a north facing window as a function of the thermal mass of the building (the building time constant parameter in GSL). The results are quite consistent for different building construction.

The switching parameters used to derive Figure 3 were obtained by running sets of simulations varying the external temperature and normal glazing illuminance as the switching parameters. This was performed for four locations (Brisbane, Sydney, Melbourne and Perth), and for all four cardinal orientations. The results obtained are summarised in Figure 5 and Table 2 for a WWR of 0.9. These figures show the energy savings obtained using the optimal switching parameters (Figure 5) and the switching parameters which give these energy savings.

**Figure 5.** The percentage energy savings for optimal switching for WWR=0.9 in each location and for each orientation. Results in all locations are similar, but energy savings are generally a little higher in Brisbane and lower in Melbourne. The savings are with respect to the same orientation for electrochromic windows in the clear state which do not switch.
<table>
<thead>
<tr>
<th>Location</th>
<th>NORTH</th>
<th>EAST</th>
<th>WEST</th>
<th>SOUTH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_n$</td>
<td>$T_{ext}$</td>
<td>$I_n$</td>
<td>$T_{ext}$</td>
</tr>
<tr>
<td>Perth</td>
<td>433</td>
<td>40</td>
<td>407</td>
<td>40</td>
</tr>
<tr>
<td>Sydney</td>
<td>401</td>
<td>40</td>
<td>367</td>
<td>40</td>
</tr>
<tr>
<td>Brisbane</td>
<td>388</td>
<td>36</td>
<td>348</td>
<td>36</td>
</tr>
<tr>
<td>Melbourne</td>
<td>473</td>
<td>40</td>
<td>430</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 2. The switching parameters giving optimal performance for the building parameters given above. $I_n$ is measured in W/m$^2$ and $T_{ext}$ is in °C.

While there appears to be a significant variation in the normal irradiance which optimises switching (for example, $I_n=369$ W/m$^2$ for a south facing window in Perth up to $433$ W/m$^2$ for a north facing window in Perth), it is important to consider the depth of the minimum in energy consumption vs $I_n$. In general these are quite shallow minima, as illustrated in Figure 6 for Brisbane. As a result, the change in performance over the range of values of $I_n$ is usually quite small, of order 2-10%.

Figure 6. The variation in energy consumption with normal intensity ($I_n$) incident on the window.

The external temperature is not a significant parameters in controlling the switching of the glazings, and from the results in Table 2 only becomes significant on western facades. This is probably because large solar loads occur on western facades when the temperatures are at their highest during the day. The optimum value for $T_{ext}$ in Brisbane is $36$°C, which is higher than any temperature experienced in Brisbane (1986 TRY year).

Source of Energy Savings

As noted above, the variation of energy consumption with window-wall ratio shows a minimum for the non-switching case for all orientations which arises from the beneficial effect of daylight in reducing the lighting energy requirements. Figure 7 shows the variations in lighting and cooling energy as the normal solar irradiance is varied between $I_n=100$ and $I_n=1000$ W/m$^2$ for Brisbane and Perth. In Perth (results shown are for a north facing window), the daylighting energy available is lower than in Brisbane (west facing window), resulting in a higher irradiance for switching. This is due to a relatively low diffuse radiation component in Perth compared to Brisbane.

Effect of Other Parameters

It is clear that the amount of daylighting which can be obtained usefully from the window plays important role in determining the optimum switching point for the window. In order to investigate how significant this is, simulations were carried out to determine the energy savings and optimum switching parameters for electrical lighting levels of 10 W/m$^2$, for lower internal loads in the building.
Figure 7. The interplay between the lighting and cooling energy which controls where the optimum normal irradiance for switching the window occurs.

(12W/m²), replacing the rear wall with an adiabatic wall (ie fully conditioned internal space), and increasing the COP of the HVAC system (form 3 to 3.4). The results, summarised in Figure 9 below, show that the lighting parameters have a significant impact on the optimum performance of the glazings in all locations and for all orientations, while the variations in the other parameters have a minimal, and almost negligible, effect on the energy savings or optimum value of $I_n$ for switching.

Figure 8. The energy saving and optimal value of $I_n$ for switching for various options in the modelled building in (a) Perth and (b) Sydney for all orientations. The results for Brisbane and Melbourne are qualitatively similar, but Perth and Sydney have been chosen as they show the extremes of clustering (Perth) and variation (Sydney). ◆ - all variations except lighting; ● - reductions in the electrical lighting energy.

There are two significant effects of reducing the lighting requirements on the performance of the building:

- a reduction in lighting energy used, even when there is no daylight; and
- a reduction in the daylight intensity which is required to initiate dimming of the powered lights.

The latter effect is largely responsible for the change in the optimum value of $I_n$ for switching, since the manner in which GSL implements daylighting means that less external light is required to satisfy the internal lighting requirements. GSL uses a very simple algorithm, developed by Aizlewood, Isaac.
and Littlefair (1996) to determine the effective lighting energy, $L$, available in the room from a window:

$$L = \frac{2W_gT_{vis}I_n}{A_w(1 - R_w^2)} \quad \text{(W/m}^2\text{)} \quad (1)$$

Where $W_g$ is the window area, $T_{vis}$ is its visible transmittance, $I_n$ is the normal irradiance on the window, $A_w$ and $R_w$ are the area and average reflectivity, respectively, of the walls of the room. No allowance is made within GSL for different reflectivities of the walls, or, more importantly, for the relative luminous efficacy of the internal luminaires and sunlight. The comparison is based on power.

CONCLUSIONS

The work performed for this study was aimed at examining how electrochromic windows can be controlled to achieve optimal performance for a particular application, and in particular to determine whether a generic switching protocol can be used for electrochromics. The results show that for a wide range of building parameters, a generic switching protocol can be used, and switching on a normal irradiance of 400W/m$^2$ provides close to optimal performance. The external temperature does not play a major role in determining when the window should be switched, as the optimum values are usually higher than the external temperatures. However, this changes significantly with the lighting power and method of control of the lighting system in the building, when the optimum value of both the external temperature and normal irradiance decrease, and the energy savings increase.

This highlights two important aspects of these results:

- calculation of the lighting levels in the building is crucial in determining the switching of the windows
- providing switching on the interior illuminance may be essential to develop a more generic switching protocol.

It should also be noted that the energy savings referred to here are energy savings which can be achieved by optimal switching of the electrochromic windows, compared to using the same glazings but not invoking switching. The actual energy savings which can be achieved compared to conventional glazings will depend on the base case glazing, and may be significantly higher than those shown here.

REFERENCES


