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Abstract

Tests of skylights made from prototype electrochromic glazings were performed in a room-sized calorimetric test facility under ambient outdoor summer conditions in Reno, NV. The test methodology and the resultant measurements of skylight heat flows and temperatures with their diurnal variations are presented. Special test issues relating to the dynamic switchable nature of the glazings are discussed.

Introduction

Switchable or "smart" glazings, which have optical properties that vary in response to some control condition, are expected to improve building energy efficiency by modifying window energy flows to match building demands. Using glazings that have variable solar or visible transmittance will allow the rejection of solar energy when its effect would be to produce unwanted air conditioning loads or glare, while accepting it when its effect is to provide useful daylight (or, possibly in residential situations, useful solar heating). The technology generally considered to have the greatest architectural potential is electrochromic glazing, i.e., glazing for which the transmittance can be varied by applying an electrical signal. (Other potential selective systems are photochromic and thermochromic.) Electrochromic glazings have been an active subject of research in a number of places over the past decade. [1] While they are not presently available with cost and durability characteristics that would make them feasible for architectural glazing, there are a number of indications that this situation may not be far off. The US Department of Energy (DOE) has recently funded a research effort to assist selected manufacturers in producing commercializable prototypes of these glazings. One of the early market applications of these glazings is thought to be in flat-glazed skylights.

As a part of DOE's research effort, we have tested some of the prototype electrochromic glazings in the Mobile Window Thermal Test (MoWiTT) Facility, an accurate, well-characterized outdoor test facility [2, 3] specifically designed for fenestration testing. We present some of the results of those tests here as a generic preview of how electrochromic glazings can be expected to perform, and of the type of problems to be addressed in assessing their performance through measurement.

The optical switching action of present electrochromic systems is primarily in the visible. Their behavior in the near infrared (NIR) varies with manufacturer; they may also switch over all or part of the NIR, be transmitting, or non-transmitting. In the visible, the material switches between a clear and a colored state. The color in this latter state varies with the type of electrochromic system chosen by the manufacturer. The most advantageous electrochromic would be one that is reflecting in its low-transmission state, since absorbed energy may still enter the building by thermal transmission, and may cause elevated glazing temperatures that produce radiative discomfort. Unfortunately, present devices are primarily absorbing in the low-transmission state. In the far infrared, properties also vary with the choice of system; some electrochromics have an integral low-emissivity coating as part of their construction, others do not (and are absorbing in that region, like glass).

Thorough study of the optical properties of the electrochromic system is an integral part of their development; therefore the optical transmittance over the terrestrial solar spectrum of a given electrochromic (at normal incidence) as a function of applied voltage is generally well-characterized. (Manufacturing reproducibility and durability of the optical properties, however, are important development issues.) But this does not suffice to determine its solar heat gain coefficient. Because the glazings are highly absorbing in the low-transmittance state (and may have a non-negligible absorptance even in the high-transmittance state), the inward flow of absorbed energy is an important effect.

In addition, from an energy-efficiency standpoint, the goal of electrochromic glazing is optimal dynamic control, which means that overall thermal performance will depend on the fraction of time spent in states of maximum, minimum or in-between transmittance. This variable aspect makes assessing performance a challenging prospect, and adds considerable interest to observing the behavior of these systems in an architecturally realistic situation.

Goals of Testing

The tests were intended to answer three specific questions about the electrochromic prototype glazings:

1. Do the glazings have switchable solar heat gain coefficient (SHGC) values reflecting their switchable optical transmittances?

2. Can the tests demonstrate the automatic control of the electrochromics and identify its effect on energy usage?

3. What are the maximum temperatures experienced by the electrochromic units in realistic operation?

In addition, there were more general questions that we hoped to address:

4. How do the electrochromic prototypes compare in performance to conventional (fixed-property) high-performance skylights?

5. How can we test the advantages of dynamic control and compare the success of different products?

6. Can we form a picture of the energy performance of electrochromic skylights and how it relates to that of fixed-property skylights?

Test Description

Glazing samples for these tests were obtained from two of the manufacturers engaged in electrochromic development. Because it was not yet possible for them to produce prototypes in approximately square-meter sizes, smaller laboratory prototypes were assembled to form a composite planar skylight glazing unit. The resulting “skylights” from the two manufacturers were denoted EC-1 and EC-2, respectively. These were mounted in a commercial skylight wood frame in place of the normal sealed-insulating glass unit. One such assembly in place for testing is shown in Figure 1; details of assembling the laboratory prototypes into composited skylight glazings are shown in Figure 2.

Figure 1. Skylights Mounted on Test Chambers. Electrochromic sample EC-2 is the near skylight, and the clear double glazed comparison sample is the far one. Due to the sizes of the EC-2 samples supplied, the skylight assemblage overlapped the frame by a few inches. The frame is sealed to the inner side of the glazing to cut off this extra area (not visible in the photograph). White sun shields shade the exterior of each skylight well adapter. Between the two skylights are a pyranometer measuring total horizontal solar irradiance, and two instruments tilted to measure total irradiance on the sample plane. One of these is a pyranometer; the other is a solar-blind pyrgeometer measuring long-wave infrared radiation. The latter is the nearer of the two instruments and has a dark dome.

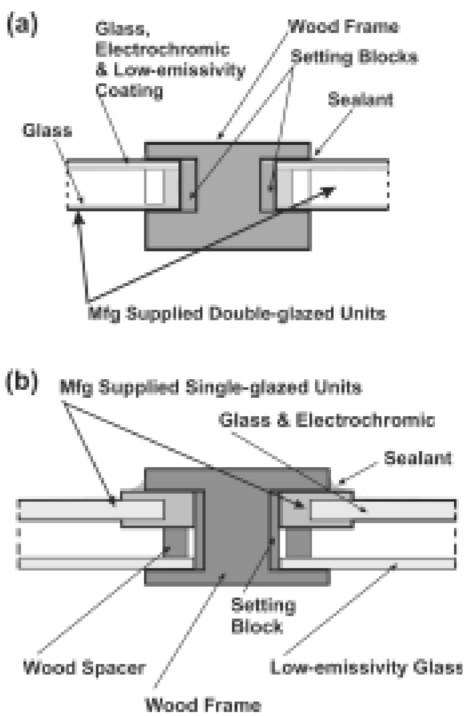

Figure 2. Details of Assembling the Manufacturer- Supplied Electrochromic Samples into a Large Glazing Unit. (a) EC-1. (b) EC-2.

All electrochromic systems effectively formed the number two surface of a low-e double glazed sealed insulating glass unit with approximately 12 mm air space. The surface numbering convention terms the surface in contact with the exterior air as number one. In one of the cases there was an integral low-emissivity coating on the number two surface over the electrochromic system. In this case the individual samples were supplied as as single-pane units, and we added a second sheet of glass with a durable low-emissivity unit. Fortunately, under the test conditions humidity, condensation and air leakage were not problems.

For each test the second chamber of the two-chamber facility held the “comparison sample,” a selective double-glazed flat skylight in a frame identical to the one holding the electrochromic assembly. All tests were simultaneous, side-by-side measurements of an electrochromic sample and the comparison sample. Since the comparison sample incorporated a proprietary coating that was both low-emissivity and selectively absorbing in the solar infrared (as well as somewhat attenuating in the visible), it provided a high-performance baseline for the tests.

The MoWiTT normally measures vertical glazings, but its design includes two openable apertures in its flat roof for testing skylights. The facility was modified for skylight testing by adding to the opening in each test chamber a commercial skylight well that is manufactured to allow skylights at an approximately 18º tilt to be adapted to a flat roof. Special provisions were made to bridge the facility’s air guard at the roof opening, and additional insulation was added to the light well and instrumentation installed to measure heat flows through the well and bridging structures. The normal vertical window sample openings were closed in the manner used to conduct “closed-box” calibration tests in the facility. A schematic cross section of the resulting test chamber configuration is shown in Figure 3. The two test chambers were configured identically, except for minor accommodations necessary to adapt to as-built construction differences. Physically the two test chambers are mirror images of one another through a plane perpendicular to the test openings rather than exact duplicates. These differences generally have no effect on the heat transfer measurements.

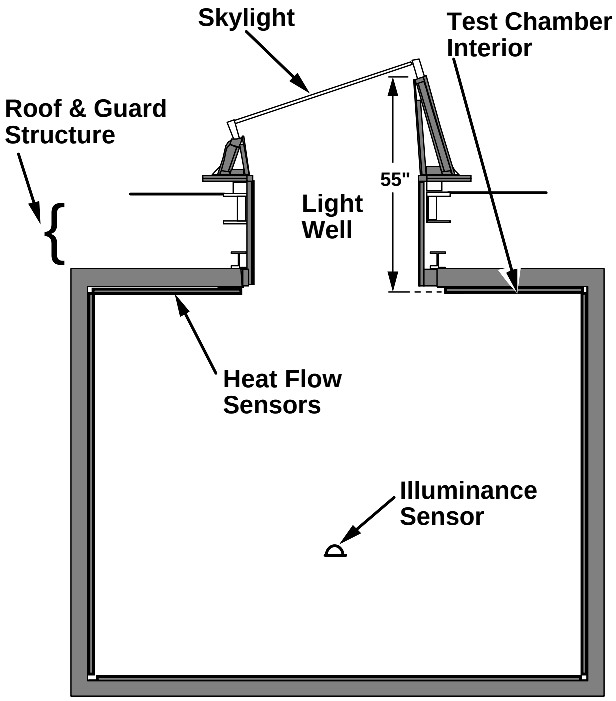

Figure 3. Cross-Section of the Calorimeter Chamber and Light Well. The overall configuration of one of the calorimeter chambers, light well, and skylight mounting is shown in a N-S vertical plane cross-section through the light well center. The interior calorimeter surface formed by the heat flow sensors defines the calorimeter control volume.

There were three tests of nominally one-week length carried out on each electrochromic/ comparison skylight pair. (Actual measurement periods varied for a variety of operational reasons, such as weather.) Two of these were static tests, during which the appropriate electrical control conditions were applied constantly to produce either (1) a fully transmissive "full bleach" state or (2) a minimally transmissive "full color" state throughout the respective test. The necessary control conditions varied with the type of electrochromic sample. During these static tests (especially the "full bleach" one) the illuminance sensor indicated in Figure 3 inside the chamber was calibrated against the control system (which utilizes a downward-looking illuminance sensor in the chamber ceiling) to determine the relation between control setting for the sample and achieved chamber work-plane illuminance. Because of direct sunlight and reflections, this relationship can at best be only an approximate one. The third test was a dynamic one in which the electrochromic control signal was continuously adjusted to maintain the chamber workplane illuminance within a band around a constant target level.

The Light Well

A cross section detail of the light well is shown in Figure 4, indicating the placement of a column of radiation-shielded air temperature sensors down the centerline of the skylight well. These were used to monitor air temperature within the well. Surface temperature measurement sensors were mounted on the interior and exterior surfaces of the skylight well and on the interior and guard surfaces of the bridging structure. Small heat flow sensors were also mounted in two places on the interior well/bridging structure surface. The exterior surface temperature sensors were shielded from direct sunlight by the white sun shields visible in Figure 1. Temperature sensors were mounted on the number one and number four surfaces of the skylight samples. The interior of the light well/bridging structure was white-painted plywood; however, to minimize optically the effect of the light well this was covered with a highly reflective specular Mylar film (nominally 98% reflectance).

While the skylight well configuration was determined primarily by constraints imposed by the facility, the resulting well is not atypical of skylight applications. Any residential application

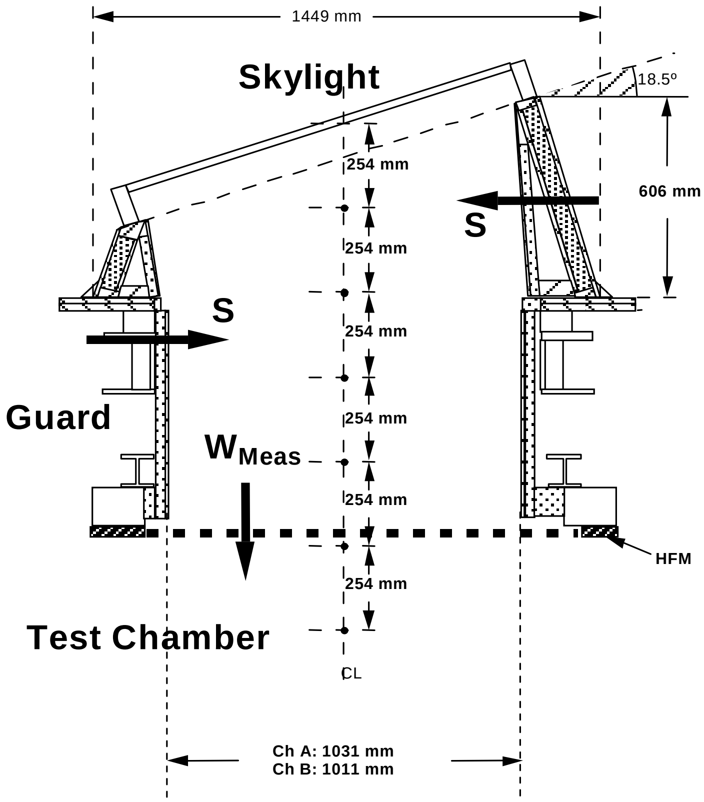

Figure 4. Detail of the Light Well and Skylight. Placement of the well air temperature sensors is indicated, as is the effective calorimeter aperture (heavy dashed line) and the heat flow WMeas crossing this aperture. The heat flow, S, through the well sides, is also indicated.

other than a room with a cathedral ceiling (a configuration increasingly discouraged by roof insulation requirements) will have a light well. For an approximately 20º roof slope a well of 1.4 m depth would imply that the skylight well is about 3.8 m from the exterior wall, a reasonable distance—especially considering the large size of this skylight, which would be appropriate to a large room. A higher roof slope would, of course, make the well depth characteristic of a smaller room. The commercial skylight adapter used in the tests is sold both for residential and commercial application. For a flat-roofed commercial building, a plenum space of a meter depth is not unusual, which would again produce a light well of a depth comparable to or larger than the one used in the tests. It is possible, but by no means inevitable, that a light well might be designed with outward-sloping sides rather than vertical ones, in order to increase light transmission of the well. This is probably more likely in residential applications than commercial. However, the greater light and direct solar transmission is more than compensated by our use of a specularly reflecting well surface. We conclude that our test conditions are not atypical of realistic skylight applications.

This is an important point, because all of our testing indicates that the presence of a light well affects skylight performance. The performance of even a simple skylight, such as a flat, clear double-glazed unit, cannot be taken as well known or easily calculable in a realistic setting. We plan to address this subject in future publications.

Heat Flow Through the Well

Each calorimeter chamber measures the total energy flowing through the aperture in its control volume, indicated by the heavy dashed line in Figure 4, and which is termed W_{eas} in the figure. This energy may consist of either conducted or convected heat, or of radiation. However, to assess the time-dependent thermal performance of the skylight, one must also consider the heat that flows through the walls of the skylight well, denoted S in the figure:

$$W(t) = W_{Meas}(t) - S(t) \cdot A_W, \qquad (1)$$

where A_w denotes the total area of the skylight well surface. While W(t) is not identical to the instantaneous energy flow through the skylight (due to storage in the well air and skylight surfaces), it is the energy flow that is relevant to the heat balance of the space. It was therefore necessary to determine S(t). To do this, the well shown in Figure 4 was divided into individual surfaces. First, the construction was divided at the facility roofline into an upper and a lower well. These are physically quite different, since the outside surfaces of the upper well are exposed to the exterior air, while the outer surfaces of the lower well are in the temperature-controlled guard space. The upper and lower wells were then subdivided into N, S, E and W faces, and each of these was instrumented with inside and outside surface temperature sensors. The upper well was surrounded with white-painted radiation shields (shown in Figure 1) that shaded both the exterior surface temperature sensors and the well exterior walls, minimizing the solar-driven heat flow into the exterior of the well. Exterior air could circulate freely behind the radiation shields. A heat flux sensor was also installed near the center of the upper north and lower south well faces, on the interior side. All of the sensors were painted to match the associated surface. (An exception to this procedure was the upper south wall, which has a very small area. Its surface temperatures were inferred from measured air temperatures).

The well heat flow was calculated as a weighted sum of the heat flow through the individual surfaces:

$$S \cdot A_W = \sum_k S_k \cdot A_W^{(k)} \qquad (2)$$

where the index *k* runs over the eight faces, S_k and $A_W^{(k)}$ are, respectively, the heat flow through and area of the k^{th} surface, and of course $A_W = \sum_k A_W^{(k)}$. The individual surface heat fluxes were calculated from a response factor series, [4, 5]

$$S_k(t) = \sum_n \left[Y_n^{(k)} \cdot \left(T_I^{(k)}(t - n \cdot \delta) - T_B \right) - Z_n^{(k)} \cdot \left(T_O^{(k)}(t - n \cdot \delta) - T_B \right) \right], \qquad (3)$$

where $T_I^{(k)}$ and $T_O^{(k)}$ are the time-dependent interior and exterior surface temperatures, T_B is a constant base temperature (25º C) that cancels out of the calculation, δ is the time step size of the calculation (here, 10 minutes) and the response factors $Y_n^{(k)}$ and $Z_n^{(k)}$ were calculated from the properties of the construction. The program WALFERF [6], which is based on a published calculation [7], was used to calculate the response factors. This program had previously been checked against both DOE2 [8] and HEATING7 [9].

The calculation was checked by comparison with the heat flow sensors mentioned above. These had been placed to sample the extreme walls: The upper north wall interior face receives direct sunlight and is located in a region of high air temperature (as will be discussed later), while the lower south wall never received direct sunlight during these tests and experiences more moderate air temperatures. The results of the comparison are shown in Figure 5 (a) for sample EC-1 at full coloration on a clear day, which represents the most extreme conditions in all of the tests. The

RMS difference between the measured data and the calculated curve in this figure is around 5 W/m^2; for the comparison sample (which represents less extreme conditions) it was closer to 2 W/m^2. For the lower south wall the corresponding figures were 2 W/m^2 and 1.6 W/m^2. Since the light well surface area is around 5 m^2, one concludes that the error inherent in the calculation is between 10 and 25 W RMS.

Figure 5 (b) shows the entire calculated well correction, $S(t) \cdot A_w$, for this day is always less than 30 W, which would correspond to an upward correction to the SHGC of 0.04. For most conditions of the tests, the well heat flow is less than half this large. We have generally neglected corrections of this magnitude for the purposes of this paper, so in general we will neglect the well heat flow in what follows.

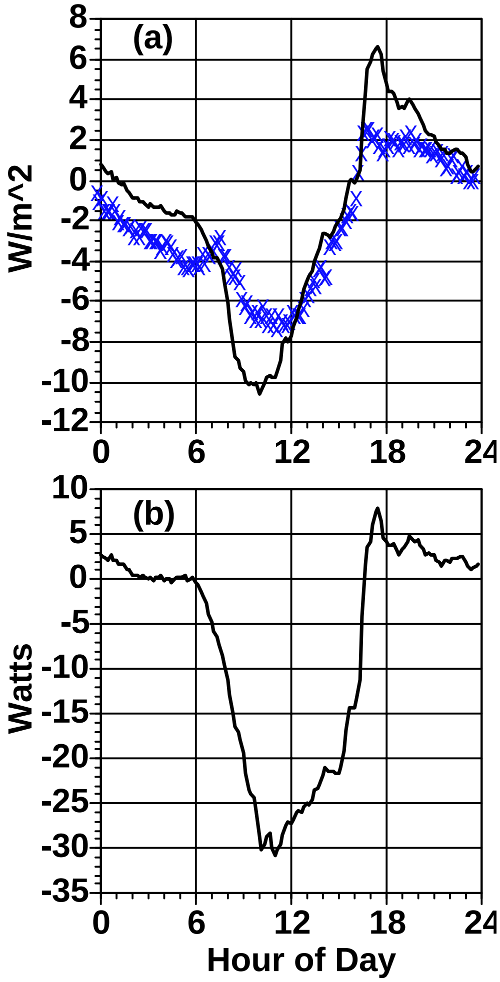

Figure 5. Determination of the Well Heat Flow, S. (a) The heat flux through the center of the upper north skylight section calculated by the response factor method (solid curve) using interior and exterior surface temperature measurements is compared with the measurements of a heat flow sensor mounted at the center of that section of the skylight well wall. (b) The calculated total heat flow, S, through the skylight well sides is shown for the same extreme day (8/13/97).

Results

Figure 6 shows the measured heat flows for sample EC-1 during the "full color" static test, in which a constant control signal sufficient to maintain the glazing in its maximally colored state, was applied.

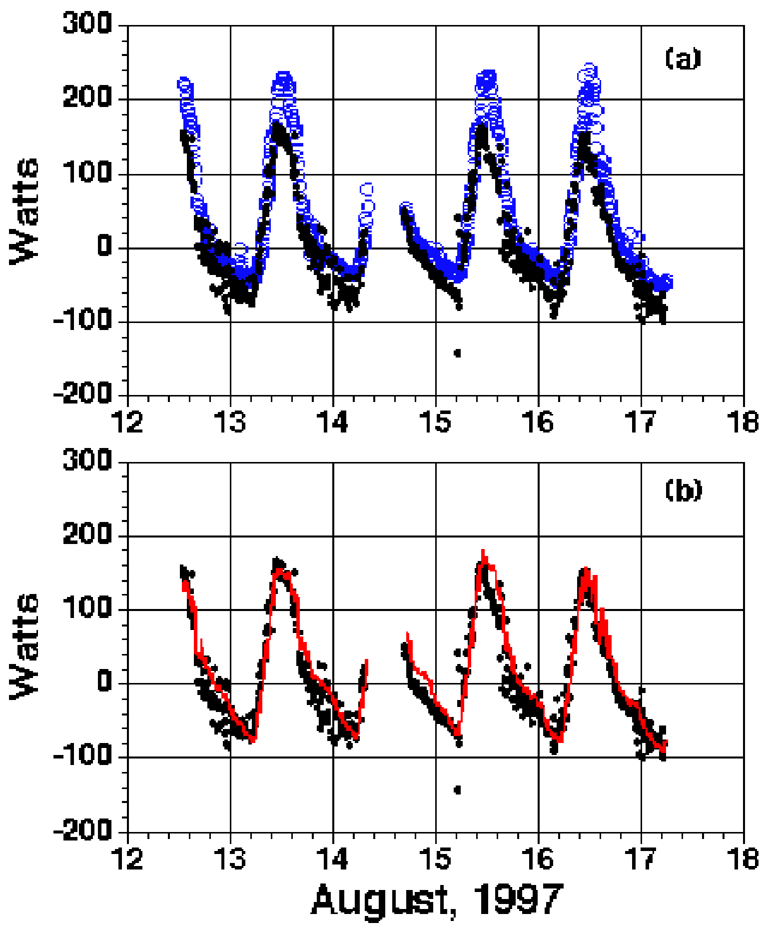

Figure 6 Heat Flows through Electrochromic Sample EC-1 in its Fully Colored State. (a) The measured heat flow W_{Meas} is compared for EC-1 (solid dots) and the comparison sample (open circles). (b) The measured heat flow through EC-1 (solid dots) is compared with the fitted function (continuous curve) used to derive the solar heat gain coefficients.

Part (a) of the figure compares the measured net heat flows for the electrochromic and comparison samples. The heat flow signs are defined such that a negative net heat flow represents a heat loss through the skylight. Since these two samples have (approximately) the same area, one can see directly from the figure that in its colored state the electrochromic sample has a somewhat lower SHGC than the comparison sample, as well as a somewhat higher U-factor (as can be seen from the larger nighttime heat loss).

This data was used to determine a solar heat gain coefficient (SHGC) for the static test by a procedure that has been explained previously. [10] Briefly, the measured net heat flow is fit with a phenomenological equation as follows:

$$W(t) = U \cdot A_T \cdot [T_{out}(t) - T_{in}(t)] + F(h) \cdot A_S \cdot I_B(t)\cos(\theta(t)) + F_D \cdot A_S \cdot I_D(t) \qquad (4)$$

where θ is the incident angle of beam sunlight on the skylight plane (i.e., the angle with the normal to the plane), I_B is the beam solar intensity (measured with a pyrheliometer), I_D is the diffuse solar intensity incident on the sample (derived from sample-plane pyranometer and pyrheliometer measurements), h signifies the hour corresponding to time t (i.e., t lies within the interval h-1/2 < t • h+1/2) and U, F_D, and F(h) (for a given h) are fitted constants. A_T and A_S are the effective sample areas for thermal and solar calculations, respectively. They may be slightly different due to the frame. F(h) is the beam SHGC averaged over a given hour, h. By calculating the average value of θ over a particular hour, h, the values F(h) determined from the fit can be reinterpreted as a function of (average) incident angle. This then gives the beam SHGC as a function of angle. Figure 6 (b) shows the fitted curve in comparison with the measurements for the "full color" test of EC-1. The fitted curve fits the measured data reasonably well, indicating that the fitted values of the constants will represent the properties of the sample, provided that the theoretical assumptions are correct.

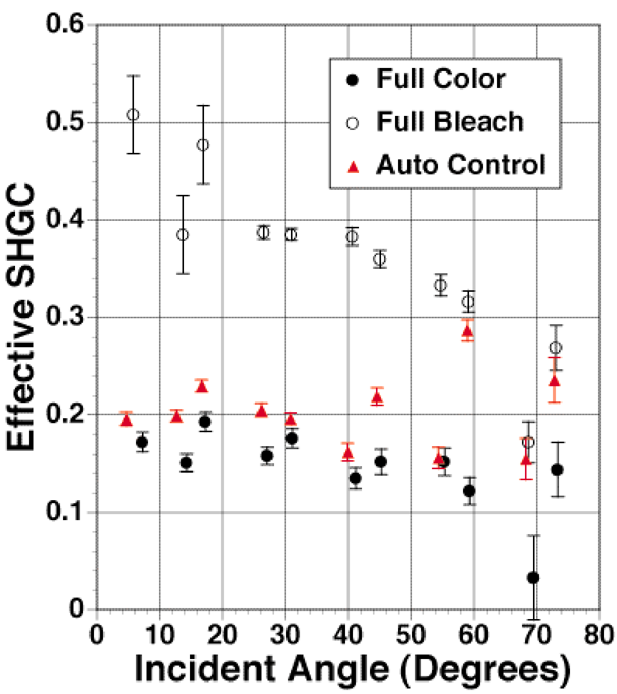

Figure 7. Measured Beam Solar Heat Gain Coefficients (SHGC) for Sample EC-1. The results from two static tests are shown, one with the sample in its fully bleached state (open circles) and one in its fully colored state (solid circles). Also shown is a test in which the coloration was dynamically controlled to maintain a constant illuminance in the test chamber (triangles).

The SHGC as a function of angle resulting from applying this procedure to the two static tests of EC-1 are shown in Figure 7. This figure clearly shows that switching the electrochromic visible transmittance from a high to a low value also produces a markedly lower SHGC. In the clear ("full bleach") state the SHGC is significantly dependent on incident angle. This is also true for the comparison sample, for which the data is not shown. In the maximally colored state there is almost no dependence on incident angle, as would be expected for a highly absorbing glazing. The error bars in this graph are for the most part derived from the statistical errors in fitting theconstants. There are in addition systematic errors, as can be seen from the somewhat jagged shape of the curve. One likely candidate for these systematic errors is the neglected well heat flow mentioned above. The large error bars on the three lowest incident angle points in the full-bleach curve include error estimates due to this effect; note the large well heat flow around noon in Figure 5 (b), which is the time at which low incidence angles occur. The more usual magnitude of 0.02 for these errors (which have not been included in the graphs) matches the irregularity of the rest of the curves. The data above 65° incidence may not be reliable; at these large incident angles, which occur early and late in the test day, a number of experimental artifacts may affect the measurement.

There is significant air temperature stratification within the light well, especially when the electrochromic sample is in its "fully colored" state, as can be seen from the plots for a single reasonably clear day in Figure 8.

In addition to its meaning for understanding skylight performance, discussed below, the temperature data is quite important for electrochromic development, since it indicates what temperatures should be utilized in durability testing. These of course depend on how dark the particular electrochromic system becomes in its "fully colored" state.

Figure 9 shows the chamber workplane illuminance measurements from several days during the tests of the electrochromic system EC-2. In order to compare the behavior of the sample for days for which the incident illuminance differed, the figure presents the ratio of the illuminance level in the electrochromic chamber to that of the chamber with the comparison glazing. For operational reasons the automatic control tests were done for two different illuminance settings; the effect of these was about the same, as can be seen from the figure. This figure clearly indicates the dynamic range of the sample in the visible, and the effect of the automatic control. It is more difficult to assess the thermal action of the electrochromic in its automatically controlled condition. Since use of equation 4 effectively averages over a number of disparate times (i.e., corresponding times on different days), the resulting average SHGC for a given incident beam angle is not very informative about the control action, since it may well be an average over different control states. We are attempting to refine our analysis to produce a true measurement of SHGC as a function of time. An alternative way of proceeding is to look at the daily net heat flow. Figure 10 shows the daily net heat flows for the tests on EC-2. In this figure each point corresponds to a single day's overall net heat flow through the electrochromic and comparison samples, with the horizontal axis plotting the net heat flow through the comparison sample and the vertical axis, that through the electrochromic sample. Unfortunately, there was significant progressive variation in weather over the course of these tests. Nevertheless, the static tests fall into two well-separated bands, with the automatic control tests falling in between, as was seen for the illuminance measurements.

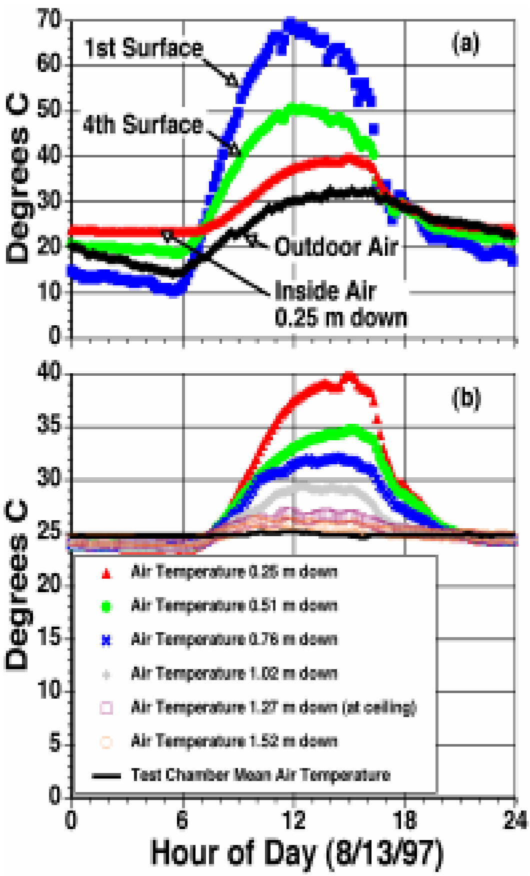

Figure 8. Measured Temperatures for Sample EC-1 in its Fully Colored State on a Clear Day. (a) Skylight surface temperatures and nearby air temperatures. (b) Air temperatures in the light well profile compared with the mean calorimeter air temperature.

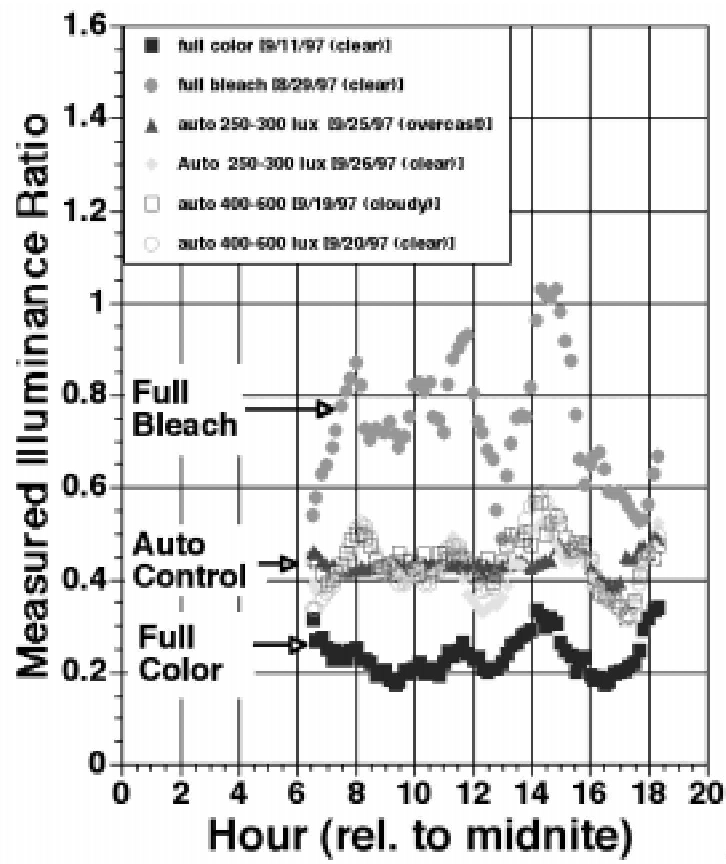

Figure 9. Constant-Daylight Operation of Electrochromic Sample EC-2. The plot shows the ratio of the reading of the illuminance sensor (shown in Figure 3) for the electrochromic sample to that in the calorimeter chamber on which the comparison sample is mounted. Four test days for which the sample coloration was controlled to maintain a constant illuminance are compared with two days of static tests (solid circles and solid squares).

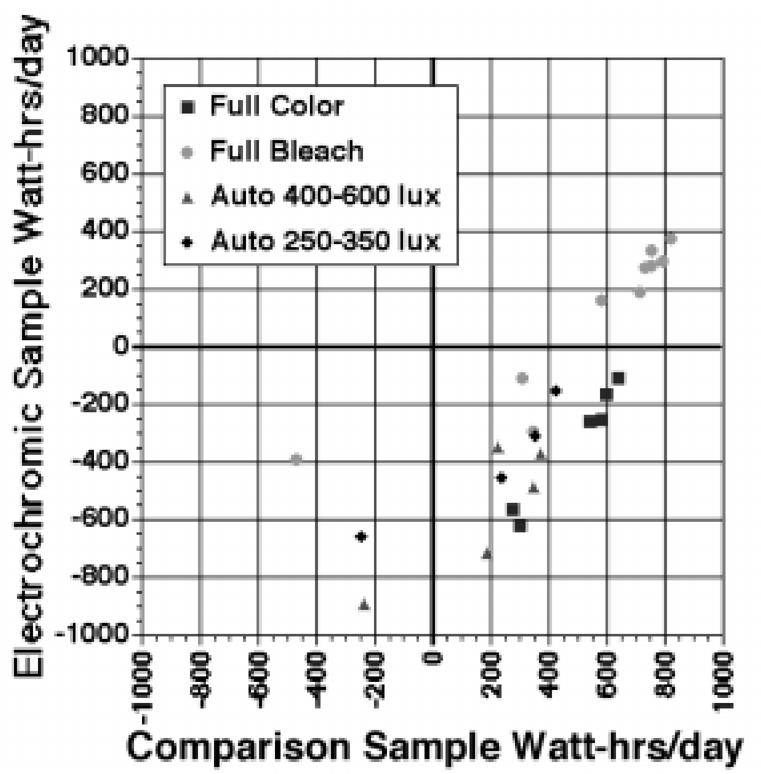

Figure 10. Daily Energy Flows Through Sample EC-2 and the Comparison Sample. The measured heat flow was summed for each complete 24-hour test day for both the electrochromic and comparison samples, and each pair of values is plotted as a point on the graph. The full-color (solid circles) and full-bleach (solid squares) static tests are compared with the two sets of automatic control conditions (triangles and diamonds).

Discussion

In general, the tests successfully answered the specific questions (1-3) posed earlier as testing goals and made an intriguing beginning on the more general questions (4-6). In some ways answering the specific questions limited the ability to answer the more general ones.

Switchability of SHGC

Figure 7 and the comparable information about EC-2 (not shown) clearly indicate that the answer to question (1) is yes; the switchable transmittance is reflected in the SHGC. Both units have a SHGC in their colored state that is markedly lower than that of the clear state. This is not at all a foregone conclusion, since the electrochromic elements are absorbing, so that the fate of the absorbed solar energy is critical to their performance in the dark state.

The Effects of Automatic Control

The answer to question (2) was also yes; the tests demonstrate the effect of automatic control, but they produced only a partial story. Figure 9 clearly demonstrates that automatic control produces an intermediate illuminance level; however, Figure 7 shows that for EC-1 the SHGC curve under automatic control is very similar to the curve for the static test in the fully colored state. The analogous plot for EC-2 (which is darker at full coloration) shows the same result. One might reasonably conclude, therefore, that the tests show no energy advantage for a switchable skylight over a dark fixed-property skylight. This conclusion would be an artifact of the choice of test conditions. In order to answer questions (1) and (3) the tests were conducted under summer conditions, when admitting solar gain represents a cooling cost. Obviously, if this were the only criterion the optimal solution would be not to have a skylight at all! The countervailing criterion is the admission of daylight. No attempt was made to weight properly the value of daylight relative to solar heat gain in these tests. (For an example of the methodology and difficulties of such a comparison, see the study on automatically controlled vertical fenestration in [11-13]). Requiring a constant-light-level control condition does implicitly assigned a value to daylight; however, the times when automatic control could produce any improvement in performance by increasing transmittance were either rare or occurred at times when it was very difficult to measure the energy impact (e.g., early morning or late afternoon). This was especially true for EC-1, where the tests occurred near the solstice and the days were uniformly clear. For EC-2 the tests extended later in the season and one can see some evidence for intermediate energy performance for the automatic control. In Figure 10, the daily energy flow for the automatically controlled tests does appear to lie between the curves for the static tests, but the data is admittedly poor. The situation is further clouded by the importance of nighttime heat loss and the fact that EC-2 and the comparison sample have significantly different U-values.

Glazing Temperatures

While a numerical answer to question (3) (which can be seen from Figure 8 to be just under 70º C for EC-1) was of considerable interest for the durability testing of the electrochromic prototypes, this value will vary with the transmittance of the sample, and especially with the minimum achievable transmittance. A more qualitative answer is more generally interesting. The temperature is considerably higher than would have been calculated from the glazing characteristics and the mean indoor and outdoor temperatures, using a heat transfer model (such as WINDOW-4 [14]). The reason for this follows from the general picture of skylight performance that can be inferred from Figure 8. If one considers the air temperature profile in part (b) at night, one sees that all of the air temperatures cluster together near the mean chamber temperature, indicating that the air in the light well is well-mixed. Since part (a) indicates that the inner skylight surface is some 4º C colder than the air 0.25 m below it, one can infer that turbulent natural convection is keeping the well air mixed, as well as making heat transfer to the skylight surface efficient. On the other hand, during the day one observes a stable thermal stratification in the well air, and, as part (a) shows, the air temperature 0.25 m below the skylight center is above the temperature of the outdoor air. Under these conditions there is no convective heat flow, and heat can go from the hot skylight inner surface to the cool chamber only by gas conduction or by radiation. In short, there is a diurnal "thermal diode" effect; the thermal resistance of the well is low for upward-flowing heat at night, but high for downward-flowing heat during the day.

This effect is not peculiar to electrochromic skylights; it occurs in any skylight, and thus the presence of a light well tends to improve the summer heat rejection. This is more effective the higher the absorption of the skylight, so it affects the performance of the electrochromic skylight in its colored state more strongly than in the clear, and it also produces much higher surface temperatures than would occur, for instance, in a vertical electrochromic window. Note that the thermal diode effect should be detrimental in winter, when solar heat gains would be beneficial.

<u>Performance Comparison</u>

One must bear in mind in considering question (4) that the tested units are pre-production prototypes, and that the eventual commercial units may have better performance. Nevertheless, comparing their performance to a high-performance conventional skylight serves to illuminate several skylight performance issues in general. Since the comparison unit contains a selective low-e coating, it has a low U-factor, relatively low SHGC, and relatively high visible transmission, a formidable combination. Both electrochromics had a lower SHGC in their fully colored state than the comparison sample (Figures 6 and 7 are indicative). They therefore produced somewhat lower cooling loads at the cost of less daylight. When automatic control implicitly assigned a value to daylight (by requiring that illuminance remain within a certain range), the cooling load advantage decreased slightly.

<u>Testing and Evaluating Electrochromic Vis-à-Vis Fixed-Property Skylights</u>

The tests provided no specific answers to questions (5) and (6), although we learned much that would be useful in designing future tests. The chief problem in forming comparative pictures of electrochromic and fixed-property skylight performance is that our understanding of the latter is inadequate. Until one can predict W(t) for a conventional skylight of known properties in a given (lossless) light well, one scarcely has a picture of performance that can be quantitatively compared with the more complicated picture for an electrochromic. Similarly, in these tests there were no specific performance advantages accruing to automatic control (regardless of the skylight properties), so question (5) was moot. We did learn that there was little point in having a linear control region. In most cases the units switched into either the clear or colored states, with negligible time spent at intermediate opacities. This is because the difference in illumination levels between cloudy and clear conditions is so large that the range of a linear controller is quickly exceeded when conditions change. In addition, under clear conditions the *thermally* optimal condition depends on the season, and is one of the extreme states: colored in summer and clear in winter. It follows that to quantify the advantages (or lack thereof) of automatic control one needs tests in both winter and summer conditions, and a reasonable sampling of non-clear conditions. One will need to count up and properly weight the amount of time the system spends in each of the extreme states, in addition to detecting any intermediate control states.

A realistic assessment of the benefits of automatically controlled electrochromic glazings also requires measuring the daylighting benefits and some means of weighing these against the thermal loads. There is some awareness of this issue for commercial applications. Consideration of related issues, such as glare and radiant thermal discomfort, does confer a benefit on the ability to moderate transient adverse conditions. Electrochromic glazings with automatic control will show an advantage if there is a penalty for overlighting; however, it is difficult to envision a situation where this is true for skylights.

Daylighting benefits are typically ignored for residential applications. This does not mean that there are no benefits, or that they have no value. The consumer decision to install a skylight (or the builder's decision to include one in a house to be offered for sale) is motivated by the perceived light amenities accruing to the skylight, and the cost of the installation demonstrates that these amenities have some economic value. The difficulty is in quantifying this value. One might argue by comparing the installation and operating costs of the skylight with those of some alternative means of providing the same level of light amenity (e.g., with an additional system of electric lights), but currently this type of argument has no credence. This may be because the alternative systems usually seem ridiculous from a consumer's perspective.

Conclusions

Tests on prototype electrochromic glazings intended for architectural applications show that the electrically controlled reductions in visible transmittance also correspond to significant reductions in solar heat gain coefficient. Electrochromic glazings give the same performance under peak summer conditions as highly absorbing low-SHGC conventional skylights, while allowing the option of greater acceptance of solar light and heat at other times.

There is a "thermal diode" effect in the performance of a skylight in a light well. Turbulent natural convection at night keeps the air in the light well thoroughly mixed and increases the interior film coefficient, while stable air temperature stratification during the daytime increases the thermal resistance of the skylight/light well combination. The air temperature stratification significantly increases the skylight surface temperatures over those that would be calculated with the conventional assumptions. Skylight temperatures in the neighborhood of 70º C were observed in the tests.

The tests examined only summer performance and only determined static properties conclusively. The specific effects of automatic control are difficult to demonstrate in tests conducted with a limited range of conditions. Both summer and winter tests, a representative selection of non-clear sky conditions, and evaluation of daylight effects will be necessary to quantify realistically the performance of electrochromics.

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