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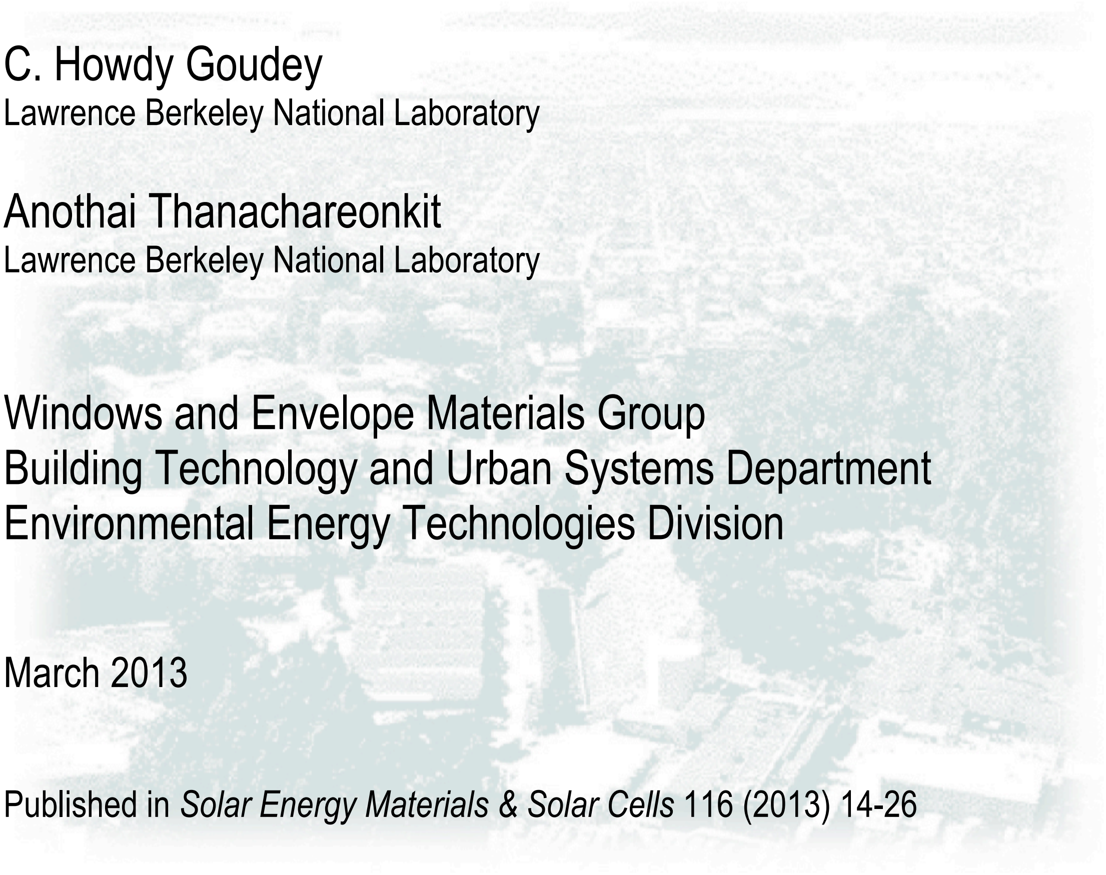

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An empirical study of a full-scale polymer thermochromic window and its implications on material science development objectives

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Abstract

Large-area polymer thermochromic(TC) laminated windows were evaluated in a full-scale testbed office. The TC interlayer film exhibited thermochromism through a ligand exchange process, producing a change in solar absorption primarily in the visible range while maintaining transparent, undistorted views through the material. The film had a broad switching temperature range and when combined to make an insulating window unit had center-of-glass properties of Tsol=0.12-0.03, Tvis=0.28-0.03 for a glass temperature range of 24-75°C. Field test measurements enabled characterization of switching as a function of incident solar irradiance and outdoor air temperature, illustrating how radiation influences glass temperature and thus effectively lowers the critical switching temperature of TC devices. This was further supported by EnergyPlus building energy simulations. Both empirical and simulation data were used to illustrate how the ideal critical switching temperature or temperature range for TC devices should be based on zone heat balance, not ambient air temperature. Annual energy use data are given to illustrate the energy savings potential of this type of thermochromic. Based on observations in the field,a broad switching temperature range was found to be useful in ensuring a uniform appearance when incident irradiance is non-uniform across the facade. As indicated in prior research, a high visible transmittance in both the switched andunswitched state is also desirable to enable reduction of lighting energy use and enhance indoor environmental quality.

*Keywords:*Thermochromic; Windows, Solar control; Building energy efficiency

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1. Introduction

Thermochromic (TC) materials transition from a clear cold state to tinted hot state at a critical temperature or range of temperatures that is inherent to the fundamental chemistry and makeup of the material. Unlike thermotropic materials which are translucent when switched, thermochromics maintain a transparent view irrespective of its switched state. These materials have been and continue to be developed for window and skylight applications as a means of passively controlling solar heat gains in buildings. The concept is to

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transmit solar radiation through the cold, untinted window in the winter to reduce heating energy use requirements and absorb then reject radiation with the hot, tinted, low-e window in the summer to reduce cooling energy use requirements. Windows are responsible for about 30% of US building heating and cooling energy use with an annual impact of 4.1 Quads (Quad = $1x10^{15}$ Btu) of primary energy use in the US [1]. Control of solar heat gains in this manner has the potential to reduce building energy use and peak electric demand, assuming that the switching response of the thermochromicmatches the typical heating and cooling demand profiles of residential and commercial buildings.

Thermochromic windows are starting to emerge on the market but very little is known about how these devices affect the energy performance and indoor environmental quality in buildings. As with any innovative technology, consumers require information in order to determine how the technology works and whether the technology provides sufficient benefits that would justify the incremental cost of the thermochromic above a conventional window. The thermochromic window has been argued to be competitive to electrochromic (EC) windows because it can provide dynamic control without the added cost and complexity of thin film electrochromic coatings: electrochromic windows require dc power and an automatic control system to capture energy efficiency benefits. Thermochromicglazings and films (for laminate applications) require neither power nor controls and would be applicable to the new and replacement windows market.

Proving energy efficiency claims at the proof-of-concept stage is hindered by a number of technical barriers. The spectral properties of TC prototypes must be fully characterized under a range of thermal conditions, so the prototype must be sufficiently stable and durable. Simulation tools must be modified to accept these data in order to model building energy performance. Field verification by way of calorimetry, mockups in outdoor testbed facilities, or installations in occupied buildings require large-area prototypes, so the prototype must be at minimum in the fabrication stage of maturity. As such, material scientists have been and are continuing to formulate new TC devices based on limited guidance as to what the optimal solar-optical properties and critical switching temperatures should be for building energy-efficiency applications.

There are two classes of thermochromic materials: inorganic and polymer based thermochromics, both of which have seen significant developments occur on the material science front recently as a result of exploiting nanoparticle composites for spectrally selective absorption [2]. Both types have been extensively reviewed in the literature [3-5], providing information on the current status of material science developments, switching characteristics of the various material formulations, and an assessment of market maturity. Near-term polymerthermochromicsexhibit absorption but remain transparent in the tinted phase, where absorption is primarily in the visible (VIS) range (wavelengths between 380-780 nm). Recently, significant R&D effort is being expended to achieve modulation in the near-infrared (NIR) portion of the spectrum (750-2500 nm) while maintaining sufficient transmittance in the VIS range. Li et al. [4] summarizes the material sciencedevelopment objectives for inorganic VO_2-based thermochromic materials, which applies in general to organic TC materials as welleven though the mechanisms for thermochromism may differ:

1) lower the critical temperature, τ_c, at which the TC transitions between semiconducting (untinted) to metallic (tinted) states from ~68°C for bulk VO_2 to a comfort temperature of ~25°C,
2) broaden the modulation of solar transmission (ΔT_{sol}), and
3) achieve a high visible transmittance in the unswitched state.

Simulation studies and prior field measurements have been used to evaluate the energy savings potential of this technology and to provide guidance to the material science community as to which properties increase energy efficiency [6-8]. Saeli et al. [7] used the EnergyPlus building energy simulation program to evaluate the energy savings potential of actual and ideal thermochromic films in a daylit office zone, showing that coatings with broad NIR switching and a low critical switching temperature (20°C) produced significant energy savings in warmer climates compared to conventional glass.

This study provides a detailed investigation of the field performance of polymer based, ligand exchangethermochromic windows for internal load dominated commercialbuilding applications. The film transitions from anuntintedclear todark tinted phase over a range of critical temperatures between approximately 24-75°C. The film can be produced using roll-to-roll processing techniques in large areas and is designed to be used as an interlayer in a laminate configuration within a low-e insulating glass unit (IGU). The thermochromic switches primarily within the visible portion of the solar spectrum.

A large-area thermochromic window was installed in a full-scale office testbed. Detailed measurements were made to characterize switching performance under variable outdoor conditions. Measured and simulated data were related to theperimeter zone heat balance and energy use for an internal load dominated office zone to illustrate how TC properties affect heating, ventilation, and air-conditioning(HVAC) energy use. Observations were made in the field concerning the appearance of the TC window when the incident irradiation was non-uniform and of its ability to control discomfort glare. Some additional observations were made relating the properties of this specific thermochromic to the three material science development objectives delineated above.

2. Outdoor field measurements

2.1. Field test set-up

A polymer thermochromicfilm was evaluated in this study. The chemistry of the ligand exchange thermochromic film that was tested is described in [5] as “the rearrangement of ligands around metal ions which cause the formation of metal complexes that increase visible light absorbance with increased temperature.” In the patent literature [9], developers describe the thermochromic in detail, where example 294 is similar in composition to what was tested (i.e., slight deviations occurred in amount of materials and type of substrate film used to improve durability and performance). Composition 294 was the only film tested and simulated in this study and is described in the patent as: “Thermochromic layers with the following compositions (Table 1) were prepared by extrusion. A 0.03 cm thick layer with Composition A was placed on one side of a separator that was 0.0076 cm thick layer of poly(ester terephthalate) which was excited on both sides by glow-discharge and labeled as Southwall "HB3/75 Glow 2-sided" available from Southwall Technologies Inc. of Palo Alto, Calif. Two layers with Composition B, totaling 0.09 cm thick, were placed on the other side of the separator. The polymer layer stack was placed between sheets of clear, plain, soda-lime float glass and a laminate was formed in a heated vacuum bag.”

Spectral normal transmittance and reflectance of Composition 294 laminated between two sheets of 3 mm, clear glazing were measured using a spectrophotometer (Perkin Elmer Lambda 950)[10]. No hysteresis was noted upon heating and cooling the sample. As shown in Figure 1, the TC exhibited switching in primarily the VIS portion of the spectrum. The Optics 5 software tool [11] was used to determine the spectral properties of the TC interlayer alone and then used with the Window 7 tool [12] to determine the optical properties of the windows evaluated in this study.

Table 1
Composition of the thermochromic film #294 used in this study.

Composition A	Composition B
0.1 m $(TBA)_2NiI_4$	0.2 m $(TBA)_2NiBr_4$
0.11 m 4-(3-PhPr)Pyr	0.4 m 1-butylimidazole
0.3 m TBAI	0.2 m TBABr
0.005 m Ph_3P	0.5 m NPG
0.07 m TMOLP	in Butvar ® B-90
1 wt% Tinuvin® 405	
in Butvar® B-90	

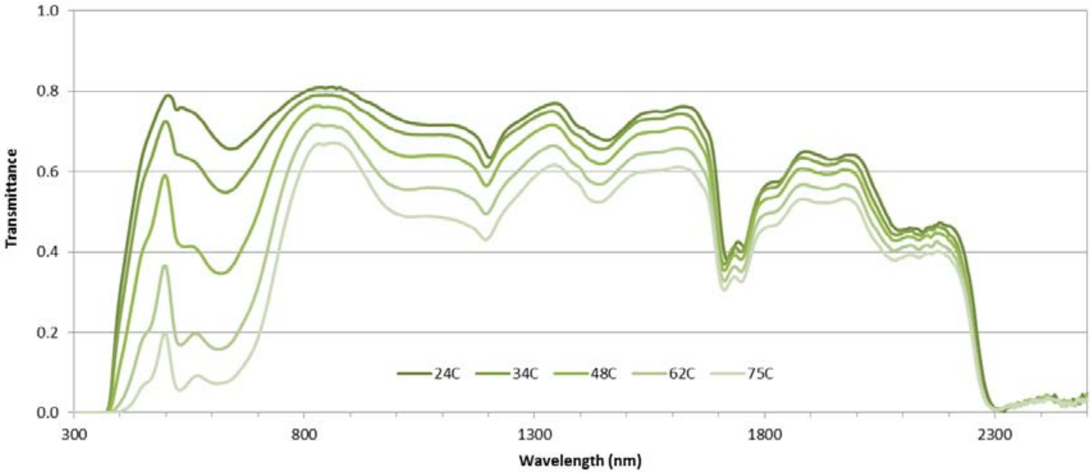

Fig. 1. Transmittance spectra of the polymer thermochromic laminate interlayer 294 placed between two 3-mm clear glass substrates at glass temperatures ranging from 24°C to 75°C.

A dual-pane clear TC window (TC2) and tinted TC window (TC3) were constructed for the field test, where the former was used in the upper portion of the window wall and the latter was used in the lower portion of the window wall. The clear TC2 window (1.35 x 0.79 m)consisted of two glazing layers: anoutboard TC polymer film laminated between two layers of clear glass and an inboard advanced spectrally-selective, low-emittance(e=0.035) glass. The spectral properties for the two glazing layers combined are shown in Figure 2. The tinted TC3 window (1.35 x 1.73 m) also consisted of two layers, but the outboard TC film was laminated between apane of spectrally selective tinted glass and a pane of clear glass with the inboard layer unchanged (also shown in Figure 2).The general makeup of the window unit (substrate materials, low-e coating, gas fill, frame details) affects energy performance but this aspect was not explored in this study.

The thermochromic windows were installed in a full-scale, south-facing, conditioned testbed office and instrumented so as to measure the visible and solar transmittance of the insulating glass unit and the temperature of the TC glazing layer. A conventional spectrally selective, low-e dual pane window was installed in an adjacent test room and used as reference. The composition and center-of-glass window properties for all windows are given in Tables2-3. Outdoor weather conditions were also monitored: direct beam and global horizontal irradiance, vertical irradiance, outdoor air temperature, and wind speed and direction. The testbed was located in a mild climate: Berkeley, California at a latitude of 37.9°N. Analysis of field results focused on the clear TC2 window, but both the clear TC2 and tinted TC3 window were evaluated using EnergyPlus simulations (Section 3).

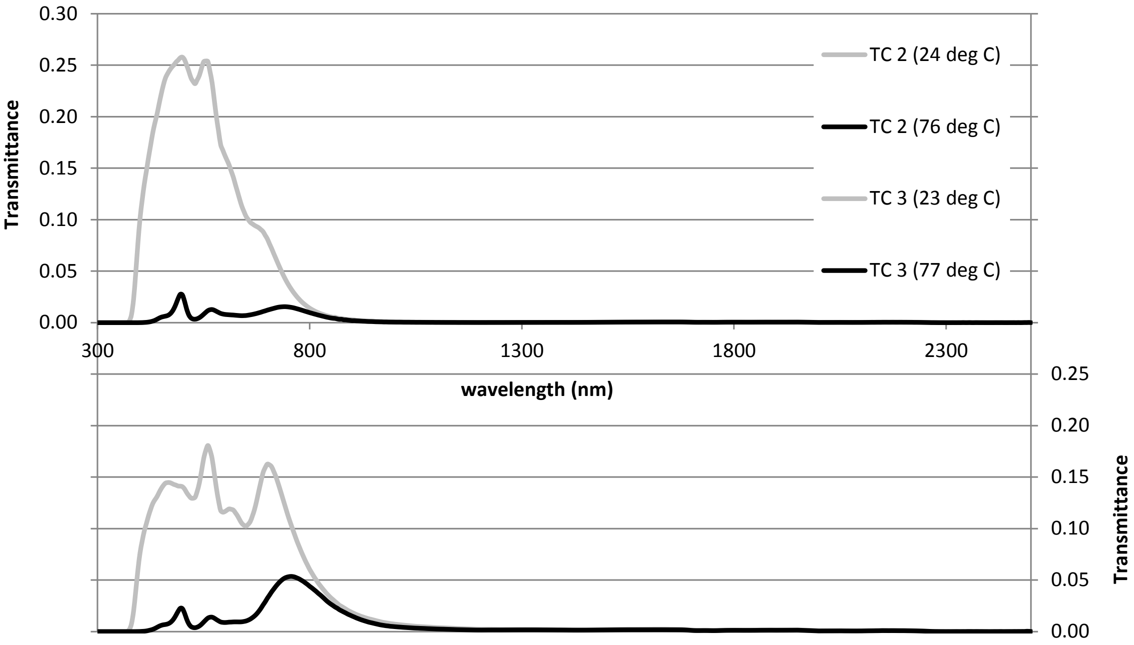

Fig 2.Transmittance spectra of the TC2 and TC3 glazing units at glass temperatures of 24°C and 76°C. Data determined using Optics 5 and Window 7.

Table 2
Composition of the windows used in the field test.

Type	Layer 1 (outside)	Gap	Layer 2 (inside)
Reference	6 mm, low-e on low-iron clear substrate, e=0.051 on surface #2	6 mm, air	6 mm low-iron clear
TC2	6 mm clear + TC interlayer 294 + 6 mm clear	10 mm, 95% argon	6 mm low-e clear, e=0.035 on surface #3
TC3	6 mm spectrally-selective tint + TC interlayer 294+ 6 mm clear	10 mm, 95% argon	6 mm low-e clear, e=0.035 on surface #3

Table 3
Center-of-glass properties of the windows used in the field test.

Type	Tgl (°C)	Tsol	Tvis	SHGC	U-value (W/m^2-K)
Reference		0.376	0.620	0.402	1.70
TC2	24	0.122	0.276	0.326	1.75
	34	0.108	0.234	0.306	1.75
	48	0.079	0.157	0.266	1.75
	62	0.046	0.074	0.218	1.75
	75	0.027	0.032	0.190	1.75
TC3	24	0.076	0.214	0.223	1.75
	34	0.066	0.182	0.209	1.75
	48	0.046	0.122	0.183	1.75
	62	0.024	0.058	0.153	1.75
	75	0.012	0.025	0.136	1.75

Note: Thermochromic properties were calculated using Window (version 6.3.9.0) and measured spectral data. Tgl: glass surface temperature of surface #2 (surface #1 is the outside glass surface); Tsol: solar transmittance at normal incidence; Tvis: visible transmittance at normal incidence; SHGC: solar heat gain coefficient. (Tgl is used instead of Tg, since Tg is typically used for the glass transition of a polymer.)

2.2. Switching profile

To characterize how the thermochromic switches, the visible transmittance of the TC2 window was measured at normal incidence by projecting light from a white light-emitting diode (LED) through the window from one side and mounting a photodetector on the other side to measure this light. The sensor provides a nominal or approximate value with an estimated error of ±0.05 and so is denoted as Tvis'. Sensors were located 38 cm from the edge of the framing.

Pyranometers (LICOR LI-200) were also installed on the outdoor and indoor vertical face of the insulating glass unit, surfaces 1 and 4, respectively, and used to measure the amount of transmitted solar radiation through the window, Qtrans. The spectral response of the cosine corrected silicon photovoltaic detector is limited to wavelengths within the range of 400-1100 nm with an error of less than 5% if measuring unobstructed daylight. As the thermochromic switches from a clear to dark tinted state, the spectral distribution of the transmitted radiation changes, affecting the accuracy of the measurement. The pyranometer readings were correlated to a reference radiometer (Huseflux SR03) with a broadband spectral response (305-3000 nm) and a correction factor was applied to the pyranometer data.The thermochromicswitches however almost entirely within the 400-1100 nm VIS rangewith minimal change in transmission occurring beyond about 1100 nm, so the readings are expected to be accurate to within about 5%. Indoor measurements were scaled to a range of 0-436.8 W/m^2 to a resolution of 0.11 W/m^2; actual monitored levels were below 130 W/m^2.

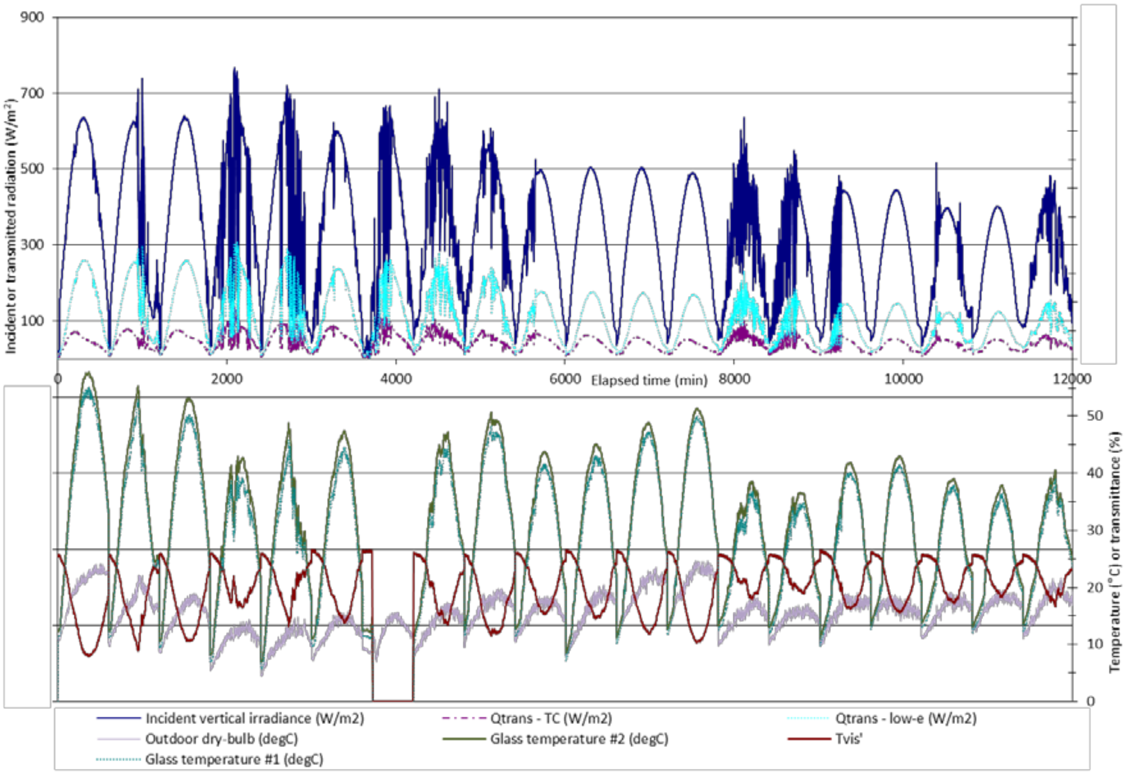

Fig. 3. Switching pattern of the clear thermochromic window in a conditioned south-facing testbed office for test days from April 1 to May 19. On the x-axis is elapsed time denoting 1-min data for each day between the hours of 7:00-17:00 Local Standard Time (ST) and on the y-axis are data pertaining to the status of the TC and the outdoor environmental conditions. The upper graph shows incident vertical irradiance, transmitted solar radiation, Qtrans, through the thermochromic and the conventional low-e windows. The lower graph shows the glass temperature for surfaces #1 and #2, nominal visible transmittance, Tvis', and outdoor dry-bulb air temperature. The indoor air temperature was maintained at an average of 24±1°C during the monitored period.

Example data are given in Figure3for test days betweenApril 1 through May 19. Switching patterns were logical. With increased solar radiation and outdoor temperature in the morning and then the reverse occurring in the afternoon, the TC2 tint level (Tvis') darkened then lightened in proportion. Peak tinting occurred a little over an hour after peak solar conditions at noon when the combined influence of both incident solar irradiance and outdoor air temperature produced the highest glass surface temperature. The TC2 window (Tsol=0.122-0.021) significantly reduced transmitted solar radiation by 33-42% compared to the reference window (Tsol=0.376) with non-coincident peak levels that ranged from 51-88 W/m^2 (TC2) compared to 122-260 W/m^2 (reference) over the monitored period. Outdoor air temperatures and levels of incident radiation were moderate: 7-25°C and up to 766 W/m^2, respectively.

Note that instead of exhibiting a pattern of solar transmission that mirrors the pattern of incident radiation over the course of the day, as is the case with the reference window, the thermochromic admits more radiation in the morning and less in the afternoon with peak levels occurring a few hours before noon. With conventional glass, HVAC engineerssize cooling systems based on peak loads that occur in the mid-afternoon so the TC window provides demand responsive benefits to the utility grid in addition to energy use reductions and could result in downsizing of chiller capacity.

Glass surface temperature measurements were made on surfaces 1 and 2 of the window using epoxy-encapsulated copper thermistors (YSI 44016, ±0.1°C) mounted with a clear RTV sealant. When irradiated, both sensor readings were greater than the actual surface temperature by approximately 1-3°C, so data are indicative of the actual temperature of the TC2 laminate. The outdoor glass surface #1 temperature was slightly lower than that of surface #2 during the day. Daytime glass temperatures(surface #2) ranged from 6-55°C over the monitored period.

Note in Figure3that the visible transmittance is inversely proportional to the glass surface temperature, mirroring its pattern with no perceptible hysteresis: the degree of switching was the same upon heating and then cooling of the TC window. Differences in Qtrans in the morning and evening can be explained by the warmer outdoor air temperatures in the afternoon.

2.3. Relationship between environmental conditions, degree of switching, and Qtrans

The empirical data presented in Section 2.2 provides an opportunity to characterize how outdoor environmental conditions dictate the glass surface temperature, the switching phase of this particularlaminated TC2window system,and the associated transmitted solar heat gains.

The measured nominal visible transmittance,Tvis', glass temperatureof surface #2, Tgl, and transmitted solar radiation, Qtrans, were correlated to outdoor environmental conditions using least squares fits, resulting in coefficients that were statistically significant (z-test>2, t- test<5%, n=5426) for the independent variables, incident vertical irradiation (Iv, W/m^2) and outdoor dry-bulb air temperature (To, °C):

$$\text{Tvis}' = -0.0000359\ \text{Iv} - 0.003653\ \text{To} - 0.00000898\ \text{Iv} * \text{To} + 0.314,\ r^2=0.68 \qquad (1)$$

$$\text{Tgl}\ (°\text{C}) = 0.0117\text{Iv} + 0.5697\ \text{To} + 0.0017\ \text{Iv}*\text{To} + 13.3,\ r^2=0.67,\ \text{surface \#2} \qquad (2)$$

$$\text{Qtrans}(\text{W/m}^2) = 0.21\ \text{Iv} + 0.38\ \text{To} - 0.007\ \text{Iv}*\text{To} + 8.51,\ r^2=0.85 \qquad (3)$$

Summary statistics for the least squares fits are given in Table4. All terms were defined by 10-min running averages since prior environmental conditions influence the window heat balance and therefore the temperature and switching status of the window. Data were filtered to eliminate times of day when shadows from local or far-field obstructions may have produced non-uniform irradiance across the façade. These fits were produced for a specific range of environmental conditions for this two month period as summarized in Table5. Indoor air temperatures were maintained at 24.2±0.11°C. Wind had a minimal influence on the fit, possibly because wind speeds were low: on average 1.3±0.7 m/s over the monitored period.

Table 4
Statistics for least squares fit to thermochromic parameters (n=5426).

		m1 Iv (W/m^2)	m2 To (°C)	m3 Iv*To (W-°C/m^2)	b	r^2	SE	error (%)
Tvis'	coefficient	-3.589E-05	-3.653E-03	-8.977E-06	0.31	0.68	0.02	10.3%
	z-test	2.65	9.28	11.14	46.95			
	t-test	0.799%	0.000%	0.000%	0.000%			
Tgl surf #2 (°C)	coefficient	0.0117	0.5697	0.0017	13.3	0.67	3.8	7.8%
	z-test	4.55	7.62	10.87	10.52			
	t-test	0.001%	0.000%	0.000%	0.000%			
Qtrans (W/m^2)	coefficient	0.210	0.383	-0.007	8.51	0.85	6.0	8.4%
	z-test	64.82	4.03	34.27	5.48			
	t-test	0.000%	0.006%	0.000%	0.000%			

Note: Percent error defined as the average percent difference between measured and predicted values.
Tvis': nominal visible transmittance; Tgl: glass surface temperature measured on surface #2; Qtrans: transmitted vertical solar irradiance; Iv: incident vertical irradiance; To: outdoor dry-bulb temperature.

Table 5
Summary of outdoor environmental and thermochromic conditions for fitted field test data

		avg	stdev	min	max
Iv	W/m^2	462.3	114.6	47.8	766.0
To	°C	16.7	3.2	6.9	24.7
Ti	°C	24.2	0.1	23.7	24.7
Wind speed	m/s	1.3	0.7	0.0	4.6
Tgl (upper east pane)	°C	41.2	6.7	23.5	57.7
Tgl (upper west pane)	°C	42.2	6.1	26.4	57.4
Qtrans (upper west pane)	W/m^2	59.3	17.1	10.5	136.2

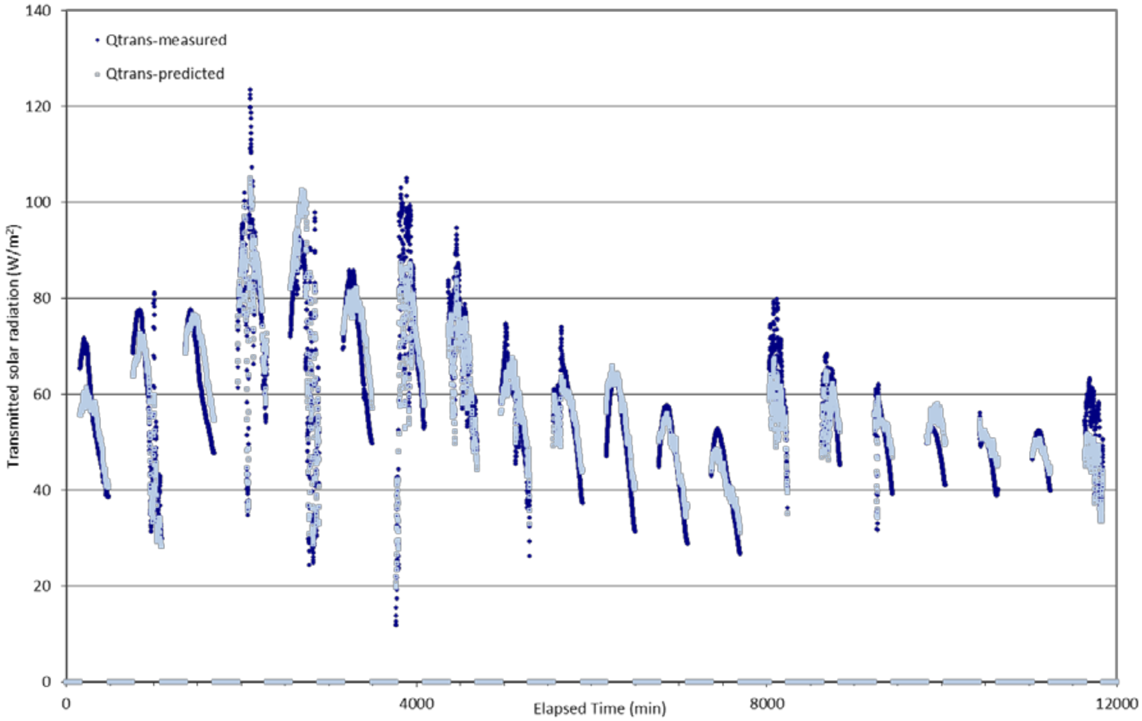

Fig. 4.Predicted versus measured transmitted solar radiation, Qtrans, through the clear thermochromic window. Predicted values were derived from field measured data for a south-facing window in a conditioned testbed office for test days from April 1 to May 19.

A temporal plot of measured and predicted Qtrans dataover several of the test days is shown in Figure4. The combined Iv*To term revealed the dependency between the two environmental variables: i.e., when it is cold outdoors but there are high levels of radiation, the thermochromicwill switch. On some days, the fit failed to capture the peaks and low ends of the monitored data. To better capture the peaks, we attempted fits to 10-min and 20-min running average or sums to determine if average or cumulative effects of outdoor air temperature and/or incident radiation had an effect on glazing temperature, TC tint level, and therefore levels of transmitted solar radiation. Incident solar radiation levels could be highly variable under dynamic sky conditions. These data were sampled once per minute in order to get an accurate depiction of sky conditions. Outdoor temperature data were also variable: there was a maximum variation of 0.2-0.4°C between 1-min time steps due to the noisy signal. Potential errors were also introduced with non-instantaneous sampling of indoor and outdoor data (although sampling of all data occurred within a 10 s sweep). The fits involving cumulative irradiation data were found to be poorer than the 10-min running averaged data. The fits between 10-min and 20-min data were found to produce almost the same degree of error.

2.4. Thermochromic properties as related to passive solar heating and solar rejection

In Figure5, predicted values are presented at defined intervals and measured values are provided as well, enabling the reader to visualize where extrapolation for the fits occurs. All predicted parameters resulting from the fits are plotted in Figure6. The predicted values are shown as a function of incident solar radiation, Iv (x-axis) and outdoor air temperature, To (8-24°C, 2°C increments). Glass temperature, Tgl, and visible transmittance,Tvis', are also given in Figure6to illustrate the sensitivity of each parameter to outdoor conditions.

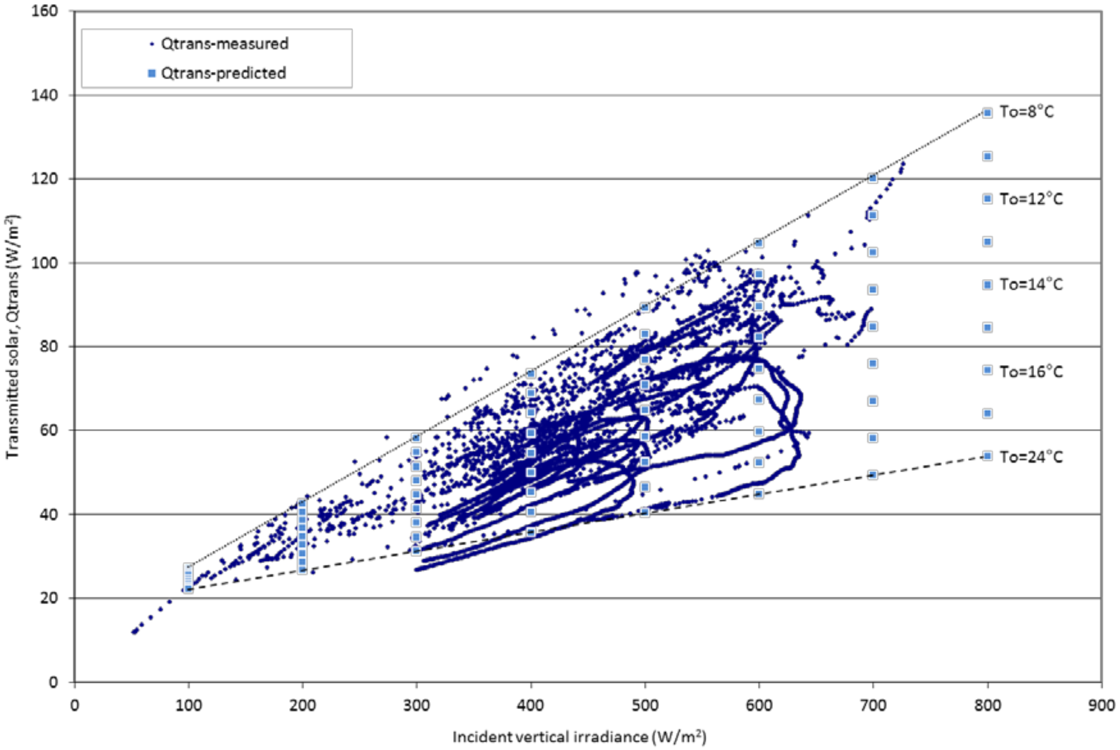

Fig. 5. Predicted and measured transmitted solar radiation, Qtrans, through the clear thermochromic window as a function of incident vertical irradiance and outdoor dry-bulb temperature, To. Predicted values were derived from field measured data for a south-facing window in a conditioned testbed office for test days from April 1 to May 19.

We can use the fits to evaluate how the thermochromiccontrols transmitted solar heat gains during the summer when it is temperate and sunny. Referring to the group of predicted values for Qtrans in Figure 6, we see that with outdoors conditions of 500 W/m^2 and 24°C, Tgl=50°C, Tvis'=0.10, and Qtrans is 40 W/m^2-glass. This is a meaningful level of solar control: for use of low-energy cooling strategies such as radiant cooling in commercial buildings, mechanical engineers strive to maintain peak perimeter zone loads below about 32 W/m^2-floor, so if this was a 4.6 m deep office zone with a large-area window (1.8 m high, window-to-wall ratio (WWR=0.50), Qtrans would contribute 16 W/m^2-floor to this load. Window heat gains from the absorbed and reradiated solar radiation and conductive heat gains would need to be added to Qtrans to obtain the total heat gains due to the window.

For summer conditions when outdoor air temperature, not solar radiation, is the main driver for switching (100-200 W/m^2, 24°C) as might occur with a north-facing window in a hot US climate, the TC2 switches less: Tgl=31-36°C, Tvis'=0.18-0.20, Qtrans=22-27 W/m^2 or 9-11 W/m^2-floor.

For winter conditions when To is low and incident solar irradiance can be high for south-facing facades (e.g., 1000-1500 W/m^2), we would need to extrapolate beyond the measured data to understand HVAC impacts in cold climates, so no example is given. However, we can deduce that switching will occur even when outdoor temperatures are moderately cold. For outdoor conditions of 500 W/m^2 and To=8°C, for example,Figure6 shows that the TC2 is partially switched as indicated by Tvis'=0.23, where 0.276 is the maximum value.

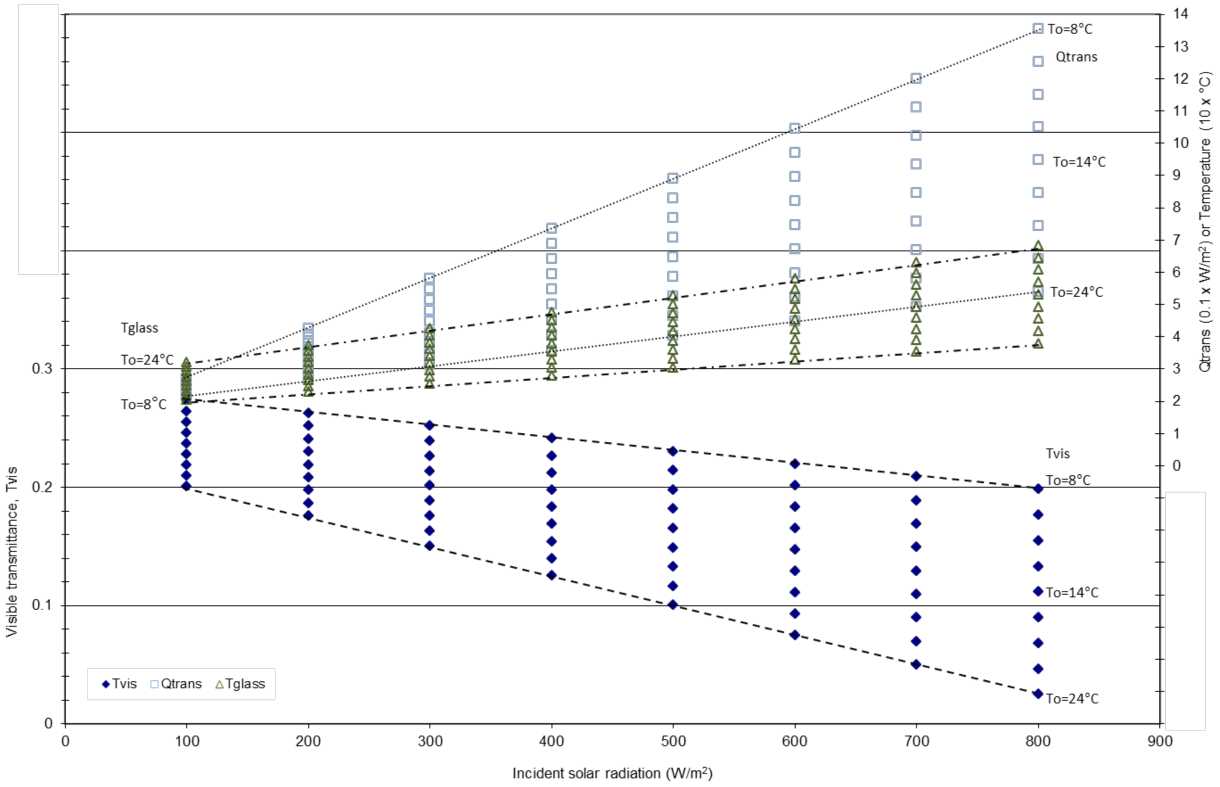

Fig. 6. Predicted nominal visible transmittance, transmitted solar radiation, Qtrans (W/m^2, divide values by 10), and glass surface #2 temperature (°C, multiply values by 10) of the clear thermochromic window based on least squares fits to incident vertical irradiation and outdoor dry-bulb air temperature. The dotted lines show lines of equal outdoor air temperature for each group of predicted values. Predicted values were derived from field measured data for a south-facing window in a conditioned testbed office for test days from April 1 to May 19.

Note that the near maximum switching level (Tvis'=0.03, Tgl=67°C) was attained when To=24°C and Iv=800 W/m^2. For this window assembly, solar irradiance effectively reduces the critical switching temperature to the target "comfort" temperature defined by [4].

The switching temperature of the TC2window *assembly*could be effectively lowered by combining the thermochromicinterlayer with an absorptive tinted glazing substrate which raises glass temperature when irradiated but this has the disadvantage of lowering the overall visible transmittance of the window.

Note that this discussion ofthermochromic window heat gains are decoupled from any particular perimeter zone load profile and HVAC system: they simply reflect independently what thethermochromicwindow will do when exposed to a limited range of outdoor conditions and a stable indoor air temperature. Because the response characteristics of thermochromicwindows are inherent with the material design (and its combination with substrate layers, low-emittance coatings, etc.), the thermochromicwindow may or may not be a good fit with the actual load profile of the building's perimeter zone. We examine this issue in the next section using the EnergyPlusbuilding energy simulation software.

3. EnergyPlus simulations

EnergyPlus (version 7.0, [13])simulations were conducted on a prototypical large office building that complied with the ASHRAE 90.1-2004 code [14], where the building characteristics such as construction, schedules, and HVAC system were derived from statistical data compiled for the existing building stock in the US then amended to meet the energy-efficiency code. At full power, the equipment power load was 8.1 W/m^2, lighting power density was 10.8 W/m^2, and occupant density was 18.6 m^2 of floor area per person. Fresh air requirements were met with a ventilation rate of 0.00051 m^3/s-m^2. The building was conditioned with a variable air volume system with an airside economizer (for the Chicago climate only). Further details on the model can be found in [15].

EnergyPlus models thermochromic windows using spectral data that have been input at regular temperature intervals over the switching range. Since EnergyPlus does not interpolate between switching temperatures, the smaller the interval between input temperatures, the more accurate the simulated values. To generate spectral data without having to resort to measurements at increments of 1°C, for example, quadratic fits were made to enable interpolation of the measured spectral data [10]. These fits were used to generate full spectral data at 2°C intervals, which were then used in Optics 5 and Window 7to produce input data for the EnergyPlus simulations. For temperatures below 24°C, the spectral data for 24°C was used; thermochromicproperties continued to change below this temperature with indications from one measurement at 15°C (where condensation affected results) that the change was small. Window 7incorporates this interpolation capability within the software, enabling the end user to generate spectral data for any arbitrary window configuration and at user-specified temperature intervals.

Figure7 shows the range of outdoor environmental conditions over the year when the perimeter zone cooling load is significant (greater than 50% of the maximum annual cooling load)due to heat gains from internal loads from equipment, people and lights, and heat flow through the building envelope (including the TC window). For this south-facing zone with a moderate-area window (window to exterior wall area ratio, WWR=0.45) in Chicago, there are many periods when it is both cold outside (< 0°C) and incident radiation levels are moderate to high (400-900 W/m^2) whencontrol of window heat gains would lead to less cooling energy use. Superimposed on this data are the cases when the TC glass temperature is greater than 48°C and the TC glazing is switched about halfway, providing cooling load control. The thermochromicwindow is able to curtail summer cooling loads but not the winter cooling loads when incident solar radiation levels are significant due to the low altitude angles of the sun. If the critical switching temperature range was lowered, annual cooling energy use could be decreased, depending on the source of cooling which may or may not incur an energy use penalty. If the HVAC system has an economizer mode, cooling is free in the winter since the system uses outdoor air, for example, and the thermochromic could be designed to reduce cooling loads during summer and swing seasons.

Site annual energy use and savings were determined for the 4.57 m deep south-facing perimeter zone for the hot/cold climate of Chicago and hot climate of Houston. Results are given for the 90.1-2004 code-compliant window (A or C), an advanced spectrally-selective low-e window (E), a triple pane insulating window (F), and the two types ofthermochromic windows (TC2 and TC3). The TC2 thermochromic window was modeled without the thermochromic interlayer (TC2') so that the benefit of the thermochromic film could bedetermined.The composition and whole window properties for the windows are given in Tables6-7. Energy use data are given in Tables8-9and shown in Figure8. The thermochromic interlayer was found to produce significant HVAC energy use reductions compared to the same window without the thermochromic (TC') – for the moderate to large-area south, east, and west-facing windows (WWR=0.30-0.60), the incremental benefit was 15-25% in both Chicago and Houston. Savings for south, east, and west facing windows compared to the 90.1-2004 code window (C) in Chicago were 20-43%, increasing with window area, and 4-22% in Houston. Data for reference windows E and F are given to benchmark performance. The thermochromic filter could be added to these reference windows to provide greater HVAC energy reductions, however the advantage of the static reference windows is the high visible transmittance, particularly window E, which is likely to reduce lighting energy use. Lighting energy savings due to daylight dimming were not quantified in this study and should be investigated in order to obtain a complete evaluation of energy performance and comfort impacts.

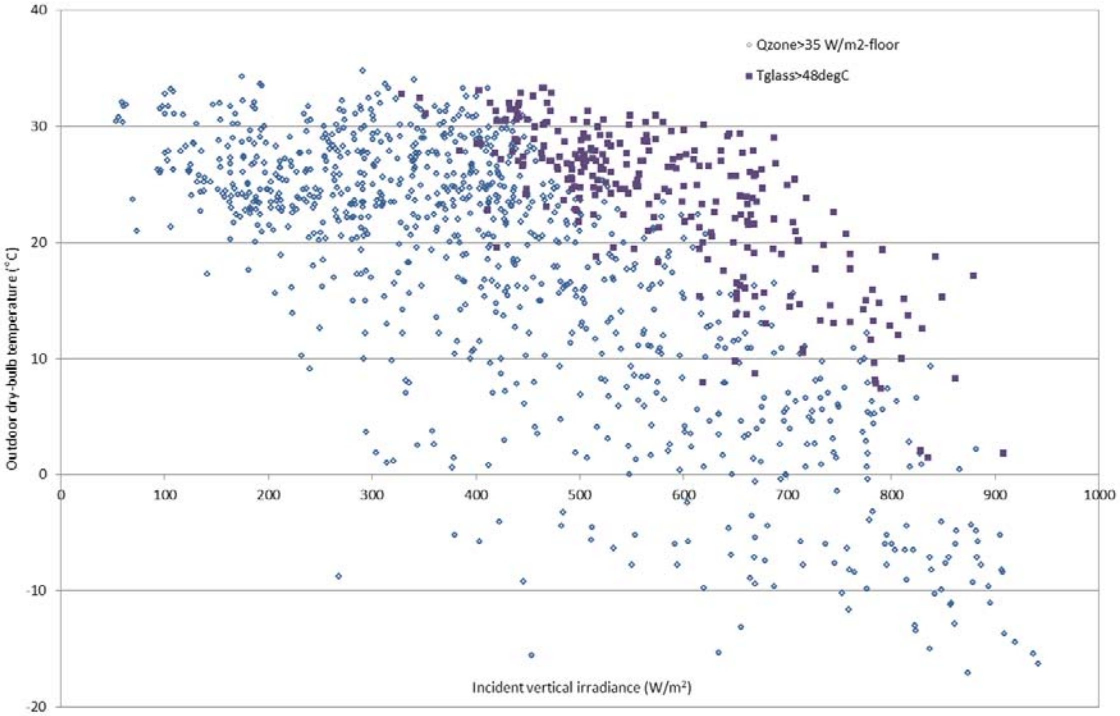

Fig. 7. Incident vertical irradiance and outdoor air temperature corresponding to hours of the year when perimeter zone cooling loads, Qzone, are significant due to both internal loads and heat flow through the building envelope, including the window. The dark square symbols correspond to outdoor conditions when the thermochromic window (TC2) is switched to about 50% of its maximum tint level. South-facing perimeter office zone, WWR=0.45, Chicago.

Table 6
Composition of windows used in EnergyPlus simulations.

	Layer 1 (outside)	Gap	Layer 2 (inside)	Gap	Layer 3 (inside)
A	6 mm clear (e=0.425)				
C	6 mm tint	6 mm Air	6 mm low-e clear, e=0.215		
E	6 mm low-e on low-iron, e=0.018 on #2	12 mm, 95% argon	6 mm clear		
F	6 mm low-e on low-iron, e=0.018 on #2	12 mm, 95% argon	suspended film, e=0.711 on #1 & #2	12 mm, 95% argon	6 mm low-e on low-iron, e=0.018 on #2
TC2'	6 mm clear + clear interlayer + 6 mm clear	10 mm, 95% argon	6 mm low-e clear, e=0.035 on #3		
TC2	6 mm clear + TC interlayer 294 + 6 mm clear	10 mm, 95% argon	6 mm low-e clear, e=0.035 on #3		
TC3	6 mm spectrally-selective tint + TC interlayer 294 + 6 mm clear	10 mm, 95% argon	6 mm low-e clear, e=0.035 on #3		

Table 7
Whole window properties of windows used in EnergyPlus simulations.

	Description	Tgl (°C)	Tvis	SHGC	U-value (W/m^2-K)
A	ASHRAE 90.1-2004 Houston		0.11	0.25	4.55
C	ASHRAE 90.1-2004 Chicago		0.31	0.4	3.12
E	Spectrally selective low-e		0.52	0.26	2.17
F	Triple pane window		0.39	0.2	1.20
TC2'	Thermochromic 2 static		0.264	0.363	2.558
TC2	Thermochromic 2	24	0.216	0.311	2.556
		34	0.183	0.289	2.556
		48	0.123	0.244	2.556
		62	0.058	0.192	2.556
		75	0.025	0.163	2.556
TC3	Thermochromic 3	24	0.181	0.234	2.191
		34	0.154	0.217	2.191
		48	0.104	0.184	2.191
		62	0.049	0.146	2.191
		75	0.021	0.125	2.191

Note: Thermochromic properties were calculated using Window (version 6.3.9.0) and measured spectral data.

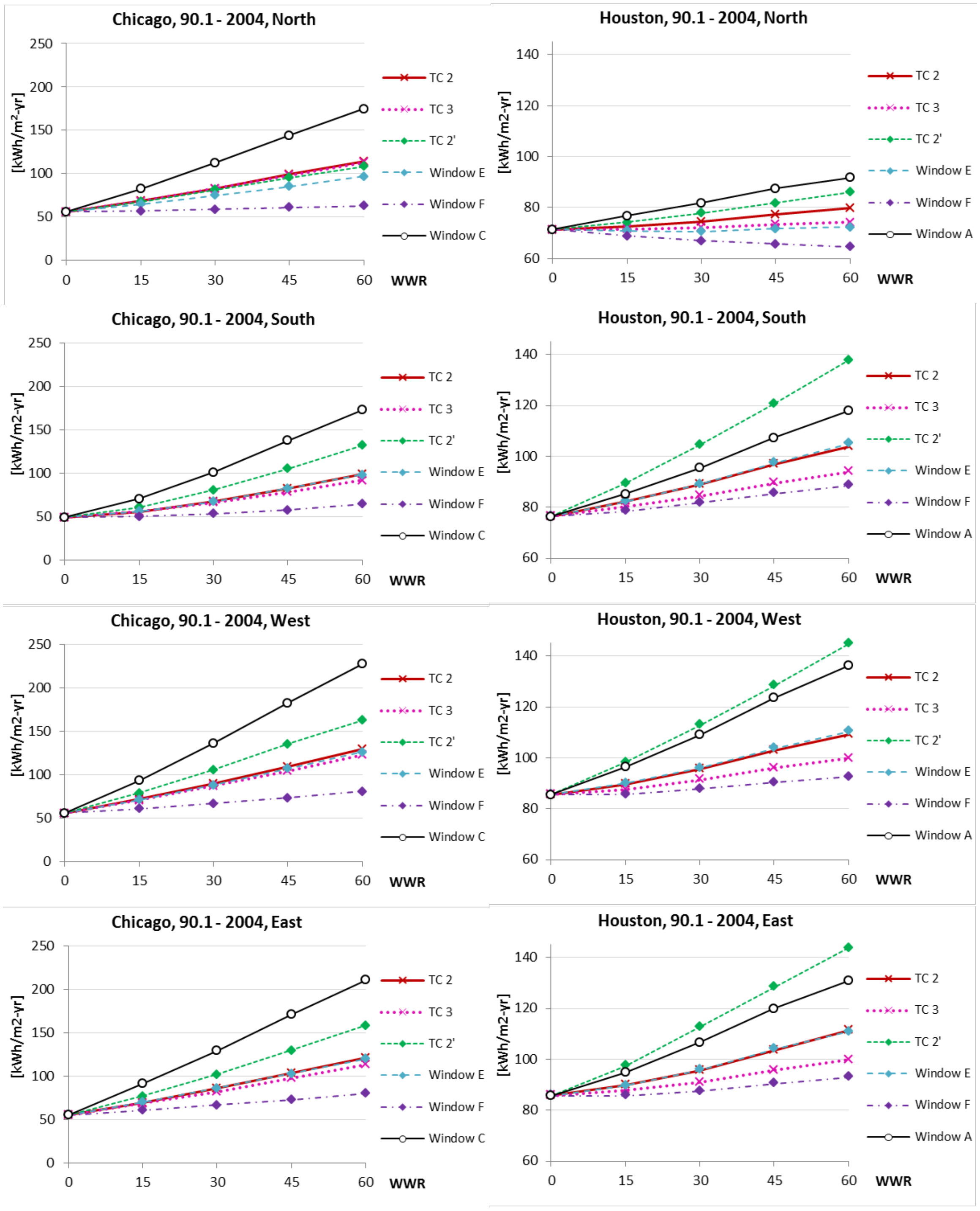

Fig. 8..Site annual energy use for a 4.57 m deep perimeter office zone in Houston and Chicago. Values are given for window-to-wall ratios (WWR) of 0 to 60% and for two types of thermochromic windows (TC2 and TC3), the same TC2 window without the thermochromic interlayer, TC 2’, the ASHRAE 90.1-2004 compliant window (A or C), and a low-e window and a highly-insulating window (F). No interior shades, no daylighting controls.

Table 8

Annual site heating, cooling, and fan energy use (kWh/m^2-yr) for Chicago.

WWR	C	TC 2'	TC 2	E	TC 3	F	d(C,TC2)	d(C,E)	d(C,TC3)
North									
0	55.7	55.7	55.7	55.7	55.7	55.7	0%	0%	0%
15	82.0	67.4	68.0	64.5	67.7	56.8	17%	21%	17%
30	112.3	81.3	82.7	74.8	82.6	58.7	26%	33%	26%
45	143.7	95.2	99.1	85.0	97.8	60.9	31%	41%	32%
60	143.7	108.2	114.0	96.5	112.9	62.9	21%	33%	21%
South									
0	49.1	49.1	49.1	49.1	49.1	49.1	0%	0%	0%
15	70.5	60.6	55.3	56.1	55.9	50.1	22%	20%	21%
30	101.3	80.9	67.2	67.5	66.4	53.5	34%	33%	34%
45	137.6	105.5	82.7	82.5	78.3	57.7	40%	40%	43%
60	137.6	132.4	99.5	98.2	91.8	64.6	28%	29%	33%
East									
0	55.3	55.3	55.3	55.3	55.3	55.3	0%	0%	0%
15	91.7	76.9	69.7	70.1	68.7	61.0	24%	24%	25%
30	129.4	102.2	85.9	86.6	82.2	66.7	34%	33%	37%
45	171.0	129.8	103.5	102.8	97.9	72.7	39%	40%	43%
60	171.0	158.6	121.4	120.0	113.9	36.5	29%	30%	33%
West									
0	55.9	55.9	55.9	55.9	55.9	55.9	0%	0%	0%
15	93.1	78.8	71.9	70.8	70.7	60.9	23%	24%	24%
30	136.3	105.7	89.9	88.4	87.0	66.9	34%	35%	36%
45	182.7	135.5	109.7	107.0	104.4	73.3	40%	41%	43%
60	182.7	162.9	129.9	126.5	122.8	80.7	29%	31%	33%

Note: d(C,TC2), as an example, is the percentage difference in energy use between window C and TC2.WWR: window-to-exterior-wall-area ratio.

Table 9

Annual site heating, cooling, and fan energy use (kWh/m^2-yr) for Houston.

WWR	A	TC 2'	TC 2	E	TC 3	F	d(A,TC2)	d(A,E)	d(A,TC3)
North									
0	71.3	71.3	71.3	71.3	71.3	71.3	0%	0%	0%
15	76.7	74.2	72.7	71.0	71.6	68.9	5%	7%	7%
30	81.8	77.8	74.5	70.6	72.2	66.9	9%	14%	12%
45	87.4	81.7	77.3	71.7	73.4	65.6	12%	18%	16%
60	87.4	86.0	79.8	72.4	74.2	64.7	9%	17%	15%
South									
0	76.4	76.4	76.4	76.4	76.4	76.4	0%	0%	0%
15	85.2	89.3	82.3	82.3	80.2	78.5	4%	4%	6%
30	95.5	104.4	89.0	89.0	84.4	81.7	7%	7%	12%
45	107.3	120.6	96.8	97.5	89.5	85.4	10%	9%	17%
60	107.3	137.6	103.8	105.0	93.9	88.5	3%	2%	12%
East									
0	85.8	85.8	85.8	85.8	85.8	85.8	0%	0%	0%
15	94.9	97.4	90.0	89.6	87.9	85.7	6%	6%	7%
30	106.6	112.7	95.6	95.9	90.9	87.5	10%	10%	15%
45	119.9	128.3	103.6	104.0	95.7	90.5	14%	13%	20%
60	119.9	143.6	111.2	110.8	99.7	93.0	9%	8%	17%
West									
0	85.6	85.6	85.6	85.6	85.6	85.6	0%	0%	0%
15	96.5	98.2	89.6	90.0	87.5	85.6	7%	7%	9%
30	109.1	112.9	95.7	95.9	91.5	87.7	12%	12%	16%
45	123.5	128.3	102.8	103.7	96.0	90.3	17%	16%	22%
60	123.5	144.8	109.2	110.3	99.8	92.5	12%	11%	19%

4. Other field observations

4.1. Breadth of switching temperature range

Non-uniform incident irradiance can produce differences in tint level if the switching range of the thermochromic device is narrow. Shadows from framing members, exterior attachments such as overhangs, or adjacent building wings can then make the tinted appearance of the façade non-uniform when the TC is in transition, which is undesirable from an aesthetic point of view. This TC system did not exhibit non-uniformity in its appearance due to its broad switching temperature range.

To illustrate the range of temperatures that could occur over a sunlit window, infrared (IR) thermography was used to characterize the surface temperature gradient across the plane of the thermochromicwindow at 15-min intervals on two sunny summer days, June 16-17, 2011. Measurements were made using a FLIR SC660 infrared camera using a microbolometer focal plane array sensor with 640x480 pixels. The sensitivity of the sensor is less than 0.03°C. The infrared camera was fitted with a 45° opening angle lens allowing it to measure a relatively wide subject area from a limited distance. IR images were taken at a position with a slightly upward view toward the sky to avoid seeing any local obstructions reflected by the window.

An example photographic image and IR image aregiven in Figure9, where only the very top edge of the window was shaded by a beam above the window and the depth of the window frame. The upper window hadthe clear thermochromic window and so was cooler than the lower window with the tinted thermochromic. The upper edge of both the upper and lower windows was significantly cooler than the center and lower regions of the window by about 10-13°C (Figure10). One can also see significant temperature differences at the junction between the glass and frame, compounded by the shadowing effect of the frame. For this thermochromic, which has a broad switching range, the change in tint level (ΔTvis=0.04) over the upper window height of 80 cm was imperceptible. Views out the window were clear and undistorted.

Fig. 9. Above: Outdoor view of the south-facing thermochromic window (middle room with the dark windows). Below: Corresponding infrared image showing the surface temperature of the windows (°C) on June 16, 12:02 PM ST.

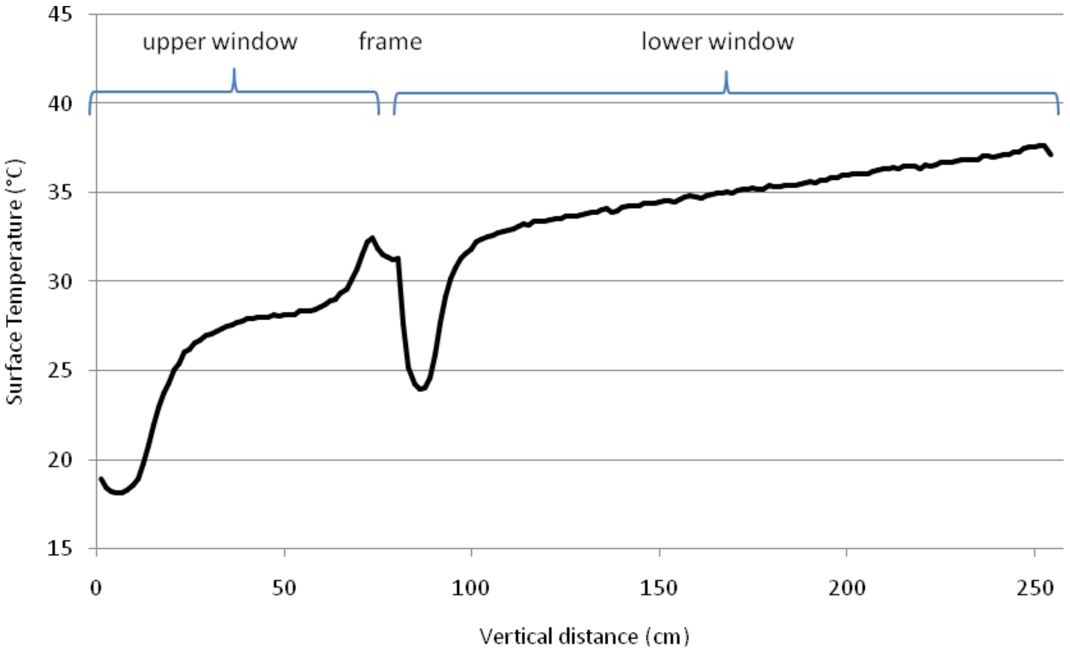

Fig. 10. Outdoor window surface temperature profile over the height of the thermochromic window wall on June 16, 12:02 PM ST. Surface temperatures were measured using infrared thermography.

4.2. Visible transmittance level as related to daylight and discomfort glare

We know from prior work that specular glazing cannot reduce the brightness of the sun orb to comfortable levels for critical visual tasks (e.g., computer-based tasks) unless the visible transmittance is very low (< 0.001) and in doing so, useful daylight is effectively eliminated. On April 6th for example (Figure11), the orb of the sun is blocked partially by the vertical mullion at the top of the window: its luminance (23,000 cd/m^2) is well over the maximum range depicted on the falsecolor scale. Note how in Figure11 sunlit patches can be seen in the photographic images of the room with thermochromic windows while the room with the interior blind has no sunlit patches. Contrast between sunlit and shadowed work areas can also be a source of visual discomfort.

Given the low Tvis range of the clear TC window in this study (Tvis=0.28-0.03), the window can however moderate discomfort glare from the bright sky. This is illustrated in Figure 11and summarized in Table10 where the visible transmittance of the TC windows at noon increases between April 6 and May 21, but is still sufficient to control luminance levels to within near acceptable levels. On April 6th, for example, the upper TC window is switched adequately to control window luminance at noon below 2000 cd/m^2. On May 21st at noon, window luminance was slightly greater than 3000 cd/m^2. The 2000 cd/m^2 threshold is an approximate threshold where a) the luminance contrast between a computer-based task (with an average monitor luminance of 200 cd/m^2) and the window is less than or equal to 10:1, a limit defined for tasks where the glare source is within one's remote field of view, and b) where it was found in an field test that there was a 50% probability that people would lower the shades when the window luminance exceeded this level [16]. Time-lapsed high dynamic range imaging was used to measure the luminance of various regions of the window within the field of view of a seated person facing the window.

The low visible transmittance levels are less likely to satisfy daylight illuminance requirements unless the window area is large. At the lower end of Tvis, the quality of the indoor environment is also likely to be gloomy. Indoor daylight illuminance levels at desk or work plane height were 683-1047lux during this brightest time of the day in the room with the thermochromic windows, where 300-500 lux is needed for typical reading and writing tasks.

Further study of these effectsis needed, however the argument for a higher range of Tvis is well founded: architects, occupants, and the real estate market value daylight, there have been studies that link daylight to improved health (e.g., combatting seasonal affective disorder, regulating melatonin, etc.), and daylight serves to reduce lighting energy use as well.

Table 10
Indoor illuminance and luminance in the thermochromic and reference test rooms at noon.

Day	Iv (W/m^2)	To (°C)	Tgl (°C)	Tvis' upper TC
April 6	638	16.6	51	0.115
May 10	442	14.9	43	0.16
May 21	401	17.8	37	0.19
Day	Iworkplane TC (lux)	Iworkplane Ref (lux)	Lwindow TC (cd/m^2)	Lwindow Ref (cd/m^2)
April 6	683	2596	1765	4241
May 10	813	1622	1922	2638
May 21	1047	1492	3049	2015

Note: Reference room has an interior Venetian blind set to a fixed blocking angle to prevent admission of direct sun. Iworkplane is given as the average workplaneilluminance in the area 3.3-4.6 m from the window. Lwindow is given for upper right hand pane of the TC2 window, facing the window from indoors.

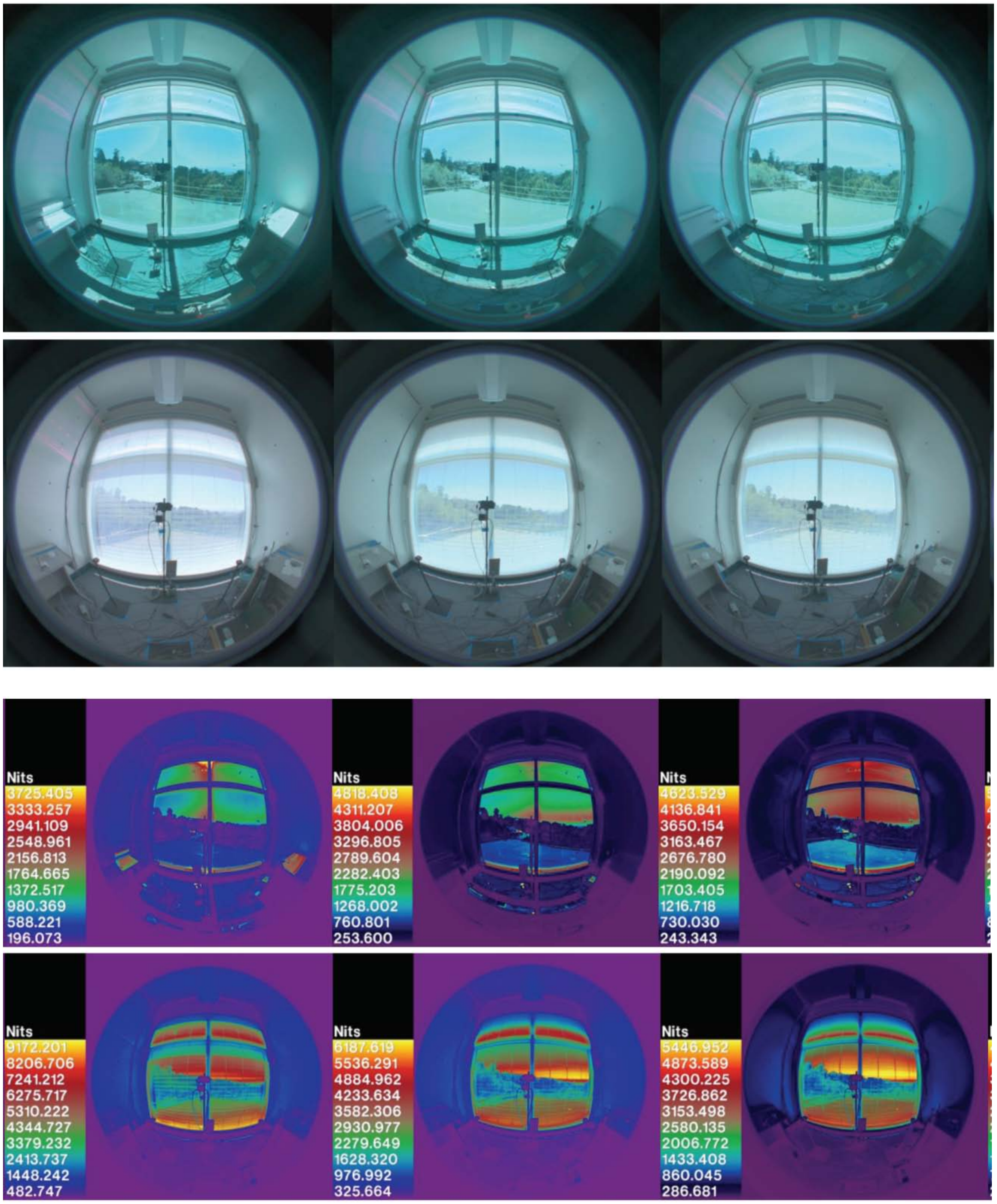

Fig. 11. *Upper images*: Fisheye photographs of the interior of the test room at noon on three clear, sunny days: April 6 (left), May 10 (middle), and May 21 (right). The upper row of images are given for the thermochromic test room. The lower row of images is given for the reference low-e window with an interior Venetian blind. The blind slat angle was positioned to just occlude direct sun. *Lower images:*Falsecolor luminance (cd/m^2 or nits) images of the same views as the upper photographs.

5. Conclusions

A field test was conducted where the performance of large-area polymer thermochromic windows were evaluated in a south-facing conditioned office testbed in a moderate climate. The TC film that was studied continuously varied transmission by a thermally induced shift in equilibrium between metal complexes of octahedral configuration to metal complexes of tetrahedral configuration through a ligand exchange process. The TC film exhibited a transparent, absorptive state when tinted. Itmodulatedsolar radiation primarily within the visible rangeof the solar spectrum over a broad switching temperature range.

The dual-pane clear thermochromic window that was field tested consisted of two glazing layers in an insulating glass unit configuration where the outdoor layer consisted of the TC film interlayer placed between two layers of clear glass and the indoor layer consisted of a spectrally selective glazing with a low-emittance coating (e=0.035). Center-of-glass properties of this window were Tsol=0.12-0.03 and Tvis=0.28-0.03 for a glass temperature range of 24-75°C. No hysteresis was exhibited by the TC upon heating and cooling of the device. The window maintained a transparent, undistorted view across its switching range. The field measured data were used to illustrate how the TC window controlled transmitted solarradiation as a function of outdoor temperature and incident solar irradiance.The TC switching response was then related to the heating and cooling demands of a typical commercial office building using EnergyPlus simulations.

Specific to the polymer thermochromic evaluated in this study:

1. Annual energy savings in the south, east, and west perimeter zones were 20-43% in the hot/cold climate of Chicago compared to the ASHRAE 90.1-2004 Standard prescriptive window. The greater the window area, the greater the energy savings. The TC window was able to produce energy savings that were greater than an advanced low-e dual pane window but less than a triple pane low-e window. Savings in hot climates were lower compared to code: 4-22% in Houston. Savings were due to reductions in HVAC energy use and did not include lighting energy use savings due to daylight dimming. Lighting energy savings due to daylight dimming were not quantified in this study and should be investigated in order to obtain a complete evaluation of energy performance and comfort impacts.

2. The polymer TC windows had a broad switching temperature range and so exhibited a uniform tinted appearance even though there were times when the distribution of radiation across the window was non-uniform. An example sunny day was used to illustrate this finding: infrared thermography indicated that a temperature gradient of 10-13°C occurred over a 80-cm wide area due to local shading by the window frame but no discernible difference in tinting was visible when viewed from the indoors or outdoors. Other TC formulations result in devices with very narrow switching ranges (e.g., 1-2°C): these will exhibit a mottled, non-uniform appearance when switching if the windows are shaded by overhangs, adjacent building wings, and other exterior near field projections.

Several observations were made that are relevant to material scientists who are continuing to develop new thermochromic materials, particularly thin film,VO_2-based thermochromic materials:

1. Thermochromic windows switch as a function of both outdoor air temperature and solar irradiance. This is generally known but may not have been clearly relayed to material scientists who may bestriving to develop new TC materials to switch at a critical temperature of 24°C, which has been defined by an ambient air temperature that people generally find comfortable. Glass temperature is not the same as ambient air temperature when the glass is absorptive and irradiated by sunlight.

2. Thinking about this a different way, the “critical” switching temperature of a TC device (defined by ambient air temperature) is effectively lowered by incident solar radiation. For example, when incident vertical irradiance was 720 W/m^2 and the outdoor air temperature was comfortable (24°C), theactual glass temperature of the polymer thermochromic that was field tested in this study was 60°C. Note that the concept of a “critical” switching temperature is not applicable to thermochromic devices with a broad switching temperature range. However, for VO_2 devices which do have a critical or threshold switching temperature (switches within a 1-2°C range), it is important to understand this concept.

3. The ideal critical switching temperature or temperature range that material scientists should design to is dependent on the characteristics of the building. Residential buildings are likely to follow the seasonal heating and cooling cycle because internal loads are low: existing thermochromic devices may be well matched to this building type. However, commercial buildings are typically internal load dominated due to the high density of people, equipment, and lighting. A south-facing perimeter office zone is often in cooling mode on a sunny winter day even in a cold climate like Chicago. The combined influence of outdoor air temperature and solar irradiance should be used to define the critical switching temperature per building type, window area, window orientation, climate zone, etc. These considerations complicate the rule set needed to develop energy-efficientTC materials. Further work is needed to develop a simple general set of criteria.

4. Current TC devices have been designed to control window solar heat gains in order to minimize HVAC energy use. These devices have a low visible transmittance even in their untinted state and will therefore reduce the amount of daylight to building interiors and potentially increase lighting energy use, particularly if the windows are small. Developing new TC materials with a high visible transmittance (i.e., Tvis=0.50-0.70) is desirable from the perspective of daylighting and indoor environmental quality (perception of brightness, connection to the outdoors). The manufacturer involved in this study has developed an alternate TC window system that admits more daylight [17] but the energy performance has not been verified. It is the belief of the authors that thermochromics should not be used to control glare and cannot be effective at controlling glare from direct views of the orb of the sun. Interior shading should be used in combination with TC windows. It is likely that the need for shading will be significantly less due to the self-regulating properties of the TC windows, allowing for greater access to unobstructed outdoor views.

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