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Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visual Comfort

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ABSTRACT

A 20-month field study was conducted to measure the energy performance of south-facing large-area tungsten-oxide absorptive electrochromic (EC) windows with a broad switching range in a private office setting. The EC windows were controlled by a variety of means to bring in daylight while minimizing window glare. For some cases, a venetian blind was coupled with the EC window to block direct sun. Some tests also involved dividing the EC window wall into zones where the upper EC zone was controlled to admit daylight while the lower zone was controlled to prevent glare yet permit view. If visual comfort requirements are addressed by EC control and venetian blinds, a two-zone EC window configuration provided average daily lighting energy savings of 10% ± 15% compared to the reference case with fully lowered venetian blinds. Cooling load reductions were 0% ± 3%. If the reference case assumes no daylighting controls, lighting energy savings would be 44% ± 11%. Peak demand reductions due to window cooling load, given a critical demand-response mode, were 19%–26% maximum on clear sunny days. Peak demand reductions in lighting energy use were 0% or 72%–100% compared to reference cases with and without daylighting controls, respectively. Lighting energy use was found to be very sensitive to how glare and sun are controlled. Additional research should be conducted to fine-tune EC control for visual comfort based on solar conditions so as to increase lighting energy savings.

INTRODUCTION

Past simulation studies have indicated that electrochromic (EC) façade systems have the technical potential to significantly reduce energy use and peak demand in residential and nonresidential buildings. Electrochromic windows can vary their tint reversibly with the application of a small applied dc voltage (gasochromic windows are of the same basic composition but switch with the insertion of an inert gas into the between-pane gap of an insulating glass unit [IGU]). Some of these studies (primarily conducted in the 1980s to early 1990s) estimated that EC windows with daylighting controls can reduce annual energy use by 20%–30% in commercial office buildings situated in moderate to hot climates if the EC window is controlled to manage daylight compared to conventional windows with daylighting controls (e.g., Sullivan et al. [1994]). Simulation studies have also been conducted to identify control algorithms that best minimize energy use in various climates (Karlsson 2001; Gugliermetti and Bisegna 2003). These studies spurred early research and development (R&D) investment in this emerging technology with the hopes that deployment of such technologies would significantly improve the energy efficiency of future building stock.

As the material science R&D on chromogenic coatings matured, moving from the laboratory producing small-area (0.075 m, 0.25 ft square) samples to pilot production facilities producing large-area (1–2 m^2, 11–22 ft^2) windows in the late 1990s, the focus of the applications side of R&D shifted from simulations to full-scale testing of pre-market devices in real-world applications in order to identify and address unforeseen engineering issues, gauge user acceptance, and measure actual energy savings under realistic weather conditions. This activity has been particularly important for the electrochromic technology because accurate solar-optical characterization of this glazing material has been challenging. Simulation tools do not yet adequately describe the various control systems or response characteristics of the technologies involved. Furthermore, automating control of switchable windows with other

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building control systems to achieve energy-efficient and comfortable conditions is yet unproven and presents very relevant challenges.

To date, several field studies have been conducted over the past few years that employed large-area electrochromic windows that were deemed sufficiently mature for market introduction. "Maturity" was defined by devices that had acceptable appearance (e.g., uniformity of tint), good potential durability, and the potential to be manufactured at low cost. In 1999, a four-month study was conducted by the Lawrence Berkeley National Laboratory (LBNL) in two private offices involving continuously modulated large-area EC windows integrated with daylighting controls (Lee and DiBartolomeo 2002). The study mapped basic characteristics of EC windows (switching range, switching speed) to monitored performance variables and presented lighting energy use savings and visual comfort data for daylight- and glare-controlled EC windows. No thermal data were monitored and the length of the study was short, providing limited information on annual performance. Within the three-year EU Switchable Facade Technology (SWIFT) program (completed in 2003), several field studies were undertaken, one for a residential application and several for typical private offices that are common to commercial buildings (Platzer 2003). These studies were undertaken to gain real-world experience with electrochromic façades (the same type used for the 1999 LBNL study) and gasochromic façades, evaluate user reactions to switchable façades, and monitor various environmental variables (interior air and operative temperatures, illuminance, and luminance distributions over a two-week period) compared to conventional windows. These field studies were limited and did not provide sufficient monitored data to confirm year-round energy use savings and comfort.

In these previous field studies, the tungsten-oxide-based (WO_3) absorptive electrochromic and gasochromic windows tested did not possess a broad switching range: i.e., the center-of-glass visible transmittance (Tv) range was $Tv = 0.50$–0.15. Earlier simulation studies identified a key drawback: tinted glass cannot block direct sun. This poses two problems: (1) occupants will experience glare discomfort if the orb of the sun is within view—unless the glass tint is almost opaque ($Tv < 0.001$) and (2) if the entire window is switched to control this direct source glare, interior daylight and lighting energy savings will be significantly reduced. The material science community has since responded by developing near-instant switchable reflective chromogenic materials that not only provide more efficient heat gain rejection but can also block direct sun by switching to a completely mirrored state. For the near-term absorptive electrochromic windows, previous energy simulation studies are likely to have provided overestimates of its energy-saving potential because the simulations were conducted with the EC window controlled for daylight optimization and not direct sun control and glare. The most relevant question of today is "by how much?"

Several studies have been conducted since these to ameliorate this situation. Under the SWIFT program, Fraunhofer Institute for Solar Energy Systems (ISE) conducted a user assessment study in two private offices with gasochromic windows installed (Wienold 2003). Twenty-seven subjects (23–35 years old) were asked to do reading, typing, and letter search tasks involving a flat-screen visual display terminal (VDT). The test conditions subjected occupants only to indirect glare (diffuse sky or indirect sunlight) within their peripheral view. Subjects rated the discomfort glare resulting from the bleached state ($Tv = 0.60$) as "just acceptable" glare, while the colored state ($Tv = 0.16$) was rated better, with "just perceptible" glare. For this view, the maximum acceptable average window luminance was found to be 5000 cd/m^2. These tests established that the EC transmittance range was adequate for controlling indirect glare. US climates tend to be much sunnier than northern European climates, so these relevant results advanced us one step closer to answering the above question.

Wienold then went on to conduct a radiance-ESP-r simulation study to estimate lighting and cooling energy use savings for electrochromic and gasochromic systems combined with a venetian blind, where the windows were controlled to block solar radiation during the summer and admit it during the winter. The venetian blind was modeled to emulate "manual" control—the blind was lowered and the slat angle was tilted to block direct sun incident on the occupant's eye and desk surface and to maintain the window luminance level below 5000 cd/m^2. Energy savings were found to be highly dependent (factors of 2–4) on the maximum acceptable window luminance threshold, and this threshold unfortunately varies among various standards, occupant views, and applications: e.g., 400 cd/m^2 for old cathode ray tube computer monitors versus 4000–5000 cd/m^2 for the modern day flat-screen low-reflectance monitors.

This field study comes to the same basic conclusion as Wienold's simulation study using control strategies tailored for the US climate and based on field data using actual EC windows and daylighting control systems: energy savings are highly dependent on how the façade system manages visual discomfort. This study presents the measured energy performance resulting from various control algorithms and façade configurations designed to mitigate direct sun and glare while providing daylight. It relies on user assessment work conducted in the same field test facility. The WO_3-based absorptive electrochromic windows tested were market-ready prototypes coupled with an immature "alpha" window controller designed to switch the EC windows to intermediate states. These EC windows have a broader switching range than those tested in previous field studies ($Tv = 0.60$-0.05, center-of-glass solar heat gain coefficient (SHGC) = 0.42–0.09). Fifteen EC windows were controlled in each of two test rooms, and their control has been integrated with a dimmable daylighting control system. Daily lighting energy use, cooling loads, and peak cooling loads were monitored over a 20-month period in a moderate, sunny climate.

METHOD

Facility Description

A new 88.4 m^2 (952 ft^2) window system testbed facility was built at LBNL, Berkeley, California (latitude 37°4'N, longitude 122°1'W) in summer 2003. The facility was designed to evaluate the difference in thermal, daylighting, and control system performance between various façade, lighting, and some mechanical systems, as well as to conduct human factor studies under realistic weather conditions. The facility consists of three identical side-by-side test rooms built with nearly identical building materials to imitate a commercial office environment (Figure 1).

Each test room is 3.05 m (10 ft) wide by 4.57 m (15 ft) deep by 3.35 m (11 ft) high and has a 3.05 m (10 ft) wide by 3.35 m (11 ft) tall reconfigurable window wall facing due south. The windows in each test room are simultaneously exposed to approximately the same interior and exterior environment so that measurements between the three rooms can be compared. Direct sun is minimally obstructed by exterior obstructions: the altitude of exterior obstructions is less than 20° for azimuth angles between 90° and 140° (0° = north) and less than 8° for azimuth angles between 240° and 270°. Interior surface reflectances of the floor, walls, and ceiling are 0.18, 0.85, and 0.86, respectively, as measured by a Minolta CM-2002 spectroreflectometer. Interior furnishings include an L-shaped desk, a flat-screen LCD monitor, and two chairs. The rooms were designated Rooms A, B, and C, with Room A to the east, Room B in the center, and Room C to the west.

Each test room is surrounded by a secondary conditioned air space that serves as a thermal guard. This guard space is designed to provide near-isothermal conditions surrounding each test room. Conditioned 0.38 m (1.25 ft) wide gaps occur between the exterior shell and test room side walls and between the side walls of adjacent test rooms. The back wall of the test rooms faces a conditioned 2.29 m (7.5 ft) wide corridor. Conditioned space occurs between the ceiling of the test room and the roof of the building. The crawlspace adjacent to the test room floors was not conditioned, but the test floor is well insulated. All exterior surfaces were heavily insulated and designed to minimize radiative and conductive heat transfer to the interior and test rooms. A packaged air-conditioning (heat pump) unit provides space conditioning to the thermal guard space. Fans are used to mix air in the gaps between the test rooms and between the test rooms and exterior shell.

Dedicated fan-coil units provide space conditioning to each individual test room. The design peak cooling load per test room was 2800 W (9560 Btu/h). The basic design of the HVAC system for each test room is as follows (Figure 2). Return air from the chamber was split into separately ducted airstreams, one of which was heated (heating duct) and the other cooled (cooling duct); these were then combined prior to re-entry to the chamber via the supply duct. The supply airflow was measured and controlled to produce an air change rate of 8–10 ACH. Total chiller capacity was sized at 10,000 W (34.1 kBtu/h chiller). Temperature-regulated chilled water was supplied by a lab chiller with a reservoir variation of less than ±0.5°C. This water flowed at a constant rate of about 1.26 10^{-4} m^3/s (2 gpm) through a heat exchanger in the cooling duct and was monitored by a turbine flow meter (Hoffer 3/8 in., linear flow range 0.75–7.5 gpm). Inlet and outlet temperatures were determined with high-stability thermistors (YSI 46016, <0.01°C drift at 70°C for 100 months). Airflow through this exchanger was controlled by a variable-speed inline fan in the cooling duct. An electric heater and an identical fan were mounted in the adjacent heating duct. The

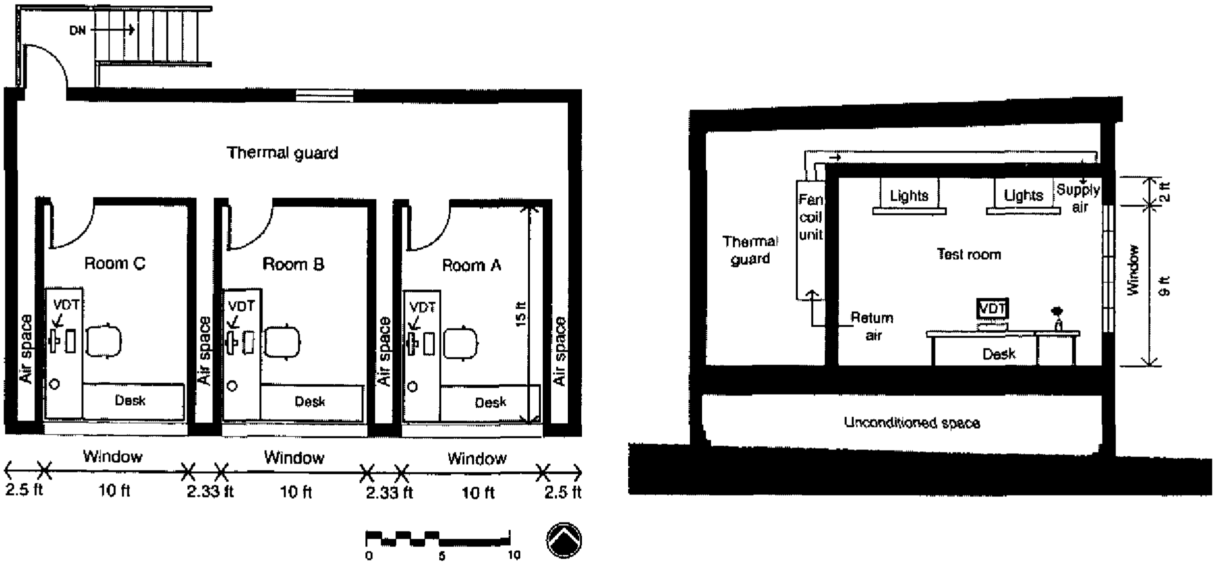

Figure 1 *Floor plan (left) and cross section (right) of test facility.*