
Mohamed Boubekri* and Nourredine Boubekri**
*Illinois School of Architecture, University of Illinois at Urbana-Champaign
**Department of Engineering Technology, University of North Texas

Abstract
The building energy consumption in developed countries accounts for 20–40% of the total energy use. Building sector in the U.S consumed about 40% of the primary energy in 2010. A significant portion of this energy is utilized to maintain thermal comfort in the buildings. A huge portion of this is lost through the windows. Smart materials have made huge advances across a broad set of architectural activities including the thermal storage and daylighting. Most of the conventional static glazing sun protection films combine reflection and absorbance of the solar infrared and UV radiation, and lead to a considerable reduction of heat during the summer months. There is a huge potential for the smart materials to be integrated to effectively optimize the building energy performance. This paper reviews state-of-the-art latest smart technologies in the area of building envelope and specifically in window glass technologies and their energy savings potentials.

Keywords: Smart Glazing and Building Skin Materials, Daylighting Design, Energy Consumption, Office Buildings

1. INTRODUCTION

1.1 Smart Glazing
The building energy consumption in developed countries accounts for 35–48% of the total energy use. Building sector in the U.S consumes about 40% of the primary energy. A significant portion of this energy is utilized to maintain thermal comfort for building occupants. Because
the building sector is the largest responsible energy consumption sector compared to others such as transportation or manufacturing, the discourse about building energy consumption and conservation is not only at the building scale but also on a larger scale that impact the global climate of our planet.

In the last three or four decades, increase of the greenhouse gases and concerns of global warming and climate change have incited legislators and consumers to call for stricter building energy codes and regulation. As a result, we have witnessed numerous advances in building design and in the various structural, envelope, lighting and mechanical systems, and in the materials used in such systems. These innovations are revolutionizing building architecture and design and lead to noteworthy reductions in energy consumption while improving building occupants’ comfort at lower cost and less energy.

This paper outlines some of these advances particularly as they relate to building envelope systems, with a particular emphasis on window glass technology.

Windows are a double edge sword in building design. On one hand, they provide views to the outside, admit sunlight for thermal comfort during the cold winter days and daylight visual comfort throughout the year for building occupants; on the other, they are a major source of heat loss. Windows account for up to 60% of thermal losses in the buildings (Gustavsen, Jelle, Arasteh & Kohler, 2007). These thermal losses and gains through the windows affects energy performance and thermal comfort in buildings. Window glazing offers transparency, at the same time, their lower thermal resistance increases the energy loads compared to opaque wall systems. Daylighting is very essential to reduce the artificial lighting and has significant impact on the occupants’ health and performance.

Smart materials have made huge advances across a broad set of architectural activities including the thermal storage and daylighting. Most of the conventional static glazing sun protection films combine reflection and absorbance of the solar infrared and UV radiation, and lead to a considerable reduction of heat during the summer months. The huge technological advancements in the windows made it possible to have dynamic tintable or smart glazing, which alters their optical properties. The adaptation of the optical properties of the glazing to the exterior conditions can be stimulated by temperature, light intensity itself or by an active electrically controlled switching mechanism.

a. **Electrochromic Glass**

Electrochromic glass change their color and opacity reversibly upon application of electric current. It is the property of chromogenic devices to alter their optical properties reversibly by an application of external potential. They vary their light transmission properties in response to voltage and, thus, control the amount of light and heat passing through them. In electrochromic windows, the electrochromic material changes its opacity. This process involves ion insertion and extraction.

The device consists of several layers: The base which is mostly glass covered by a transparent conducting film, Ion storage layer / cathodic electroactive layer, Ion Conductor / electrolyte, and
Electrochromic layer (Fig. 1). The multilayers are designed to allow the storage of ions and their movement back and forth for the insertion and extraction from the electrochromic layer, when the electric potential is applied.

When electric potential is applied between the transparent electrical conductors, ions travel from one layer to another, where a reversible solid-state change takes place, causing the layer to tint and absorb light. Reversing the applied voltage causes the ions to migrate back to their original layer, and the glass returns to its initial clear state. This field switches the glazing between a clear and transparent Prussian blue translucent state, offering similar view levels.

The electrochromic effect occurs in certain inorganic materials, including transition metal oxides (TMO), oxides of tungsten, molybdenum, titanium, niobium, vanadium, iridium, cobalt and nickel. (Ferrara & Bengisu, 2014)

Figure 1: Mechanism of Electrochromic windows

Typical electrochromic glass have an upper visible transmittance range of 0.5 to 0.7 and a lower range of 0.2 to 0.25. The solar heat gain coefficient ranges from 0.1 to 0.5. Lower transmission is desirable for control of radiation transmission, glare, and overall visual comfort. High transmission is desirable for daylight during cloudy days. Therefore, the greater the range of
transmission, the more able the window is to satisfy a wide range of daylighting and HVAC requirements.

There are two types of electrochromic windows: Polymer dispersed liquid crystal (PDLC), the most frequently used, and Suspension particle device (SPD).

**Polymer Dispersed Liquid Crystal Glass**

Liquid crystal glazing is the use of glass that allows to switch between transparency and translucence through the passage of electric voltage through it (Fig. 2). The technology usually applied in the windows is polymer dispersed liquid crystals (PDLCs). These windows have liquid crystals, which respond to an electrical charge by aligning them parallel and, consequently, letting light through. When the electrical charge is absent, the molecules of the liquid crystals in the window are randomly oriented reducing the transparency of the glass. With this technology, the glass is either clear or translucent. There are no intermediate settings. They require power to exhibit clear transparency.

A PDLC consists of a laminate system of laminate glass panes which include two substrate layers coated on the inner sides with a transparent conductive oxide to serve as electrodes, (enclose a polymer matrix, in which the microscopic molecules in the polymer matrix are dispersed are embedded in a random order) this part is not clear. When voltage is applied, the molecules arrange themselves parallel to the light and allows the light to pass through the glass.

![Figure 2: Mechanism of Polymer Dispersed Liquid Crystal glazing (PDLC)](image-url)
Typical PDLC devices have a light transmittance factor of 60-80% in active state and 40-60% in inactive state. Solar transmission is around 80% in the OFF state and in between 44–60% in the ON state. They are not effective in reducing IR transmission.

*Suspended Particle Devices Glass*

This device is controlled electrically and utilizes a thin, liquid-like layer in which numerous microscopic particles are suspended. (Fig. 3)

The SPD windows consists of two glass panes on each side with transparent conductive material coatings on the inside. There are two layers of liquid suspension film with Suspended molecular particles in a solution. This molecular particles move randomly and collide in their natural state, thereby blocking the direct passage of light. When energized, the particles align rapidly and the glazing becomes transparent.

This switchable glazing could block up to 90% of the visible light in its active state. It has minimum impact on the transmitted radiation.

*Figure 3: Mechanism of Suspended Particle Device glazing (SPD)*
b. Thermochromic / Thermotropic Glass

Thermotropic glazing is one of the smart glazing technologies which require heat energy for it to activate. Heat, instead of electricity, actuates this glazing. When the critical temperature is exceeded, they exhibit temperature dependent change of the light scattering properties. Researchers point out that “If the increased scattering is linked with a substantial degree of back scattering dependent on the temperature increase, the materials are suited for an application in solar control.” (Seeboth, Ruhmann & Mühling, 2010) Thermotropic effects could occur by a phase separation process, by a phase transition between isotropic and an anisotropic state, and strongly differing temperature dependencies of the refractive indices (RI) of domains and matrix.

In unswitched state, the thermotropic layer is transparent for visible light. If the temperature is raised above the switching point, the layer becomes white, the transmittance drops and no more visual contact to the surroundings is possible.

The advantages of these passive switching materials are the fact that they are self-regulating, they have a high switching range, there is no additional energy consumption required such as in the electrochromic case, they have term stability and they come with a relatively low cost compared to other switchable glazing technologies.

These systems consist of at least two components with different RIs. The difference in RIs has no effect because all components are homogeneously mixed at a molecular level or have similar RIs at temperatures below the switching point. The combined material has a median refractive index and is highly transparent for solar radiation in this state. A difference between the refractive indices of both components appears due to a phase separation or phase transition upon reaching the switching temperature. As a consequence, scattering domains of dimensions similar to solar wavelengths take effect. The solar radiation is scattered at the interface between both components. The incident solar radiation is reflected (back scattering). In view of the best possible solar light shielding properties, a high back scattering (reflection) efficiency is required.

Four different switching mechanisms for thermotropic systems (Fig. 4) (Seeboth, Ruhmann & Mühling, 2010)

- Phase separation (e.g., polymer blends and polymer gels with “Lower Critical Solution Temperature”)
- Change of the particle size (e.g., thermotropic nanoparticles)
- Aggregation (e.g., block copolymers)
- Phase transition (e.g., casting resins with fixed domains)
The materials used in thermotropic applications are as follows:

- Phase-Separating Polymer Blends and Thermotropic Gels
- Thermotropic Nanoparticles and Aggregates
- Polymer Blends with Phase Transition
- Thermotropic Casting Resins
- Thermotropic Polyolefine Films

One of the main advantages of smart switchable glazing materials is the control of daylight penetration for energy saving considerations while not neglecting visual comfort requirements. Often designers focus too much on the energy aspects and ignore building occupant behavior. When the design solutions fail to meet visual comfort needs of the users, these latter alter their condition of their living or working condition which often leads to the failure of the original design intent. In case of sunlight conditions, window glass alone, whether smart or not, may not be sufficient to meet visual comfort requirements without the use of additional shading devices such as overhangs, louver systems, or other types of shading systems. A simulation study...
conducted to evaluate lighting energy savings of split-pane electrochromic (EC) windows controlled to satisfy key visual comfort parameters found that the energy performance of electrochromic windows depended on how louvers were controlled, manually or automatically. Hourly adjustment of the louver system resulted in higher lighting energy savings. The use of blind proved to be better than a fixed overhang. Electrochromic windows offered an additional advantage compared to non switchable glazings which is that on an annual basis they allowed less obstruction and more view out compared when louvers are applied automatically (Fernandes et al., 2011).

1.2. Phase Change Materials (PCMs)

All materials can exist in various physical states: gaseous, liquid and solid, which are known as phases. The temperature changes or pressure in the environment cause breaking of molecular bonds in the structure of the material, which leads to the change of physical state (phase) of material, the so-called phase change. They can reversibly store/release heat energy, as a response to temperature changes in their surroundings. One of the most known phase change material is water which freezes at 32 degrees F and thaws above it. It also transforms into water vapor at high temperature.

PCM usually have low thermal conductivity, and can act as self-insulators. Some PCMs have poor thermal conductivity and good visual light transmittance, these materials can be used as transparent insulation and also to store the heat. These are highly transparent for the visible part of solar spectrum whereas the infrared part is absorbed within.

The two main types of PCM used in building construction are inorganic salt hydrates and organic paraffin or fatty acids. The third type is a combination of organic and inorganic substances, called Eutectics.

PCMs are particularly suitable for applications in buildings, generally rise in temperature during the working day, through the heat load generated by people and equipment, but can be cooled when not in use.

Some insulation materials are made of PCM. Much like water, PCM apply the same concept of storing and releasing energy in water, but have moved the transition temperature from 32 degrees F to the mid-70s. Fig.5 shows an example of a bio PCM installed in ceiling application that works day and night to stabilize indoor temperatures depending on the outdoor temperature. It is designed to release heat into the outside when the outside temperature is too excessive above a prescribed range, or release heat into the space when the indoor temperature is below the prescribed range.
1.3. Air Cleaning Paint

Air cleaning paint with crystal active photocatalytic technology uses light energy to break down noxious air pollutants and convert them into less harmful substances (Fig. 6). Any surface coated with this type of paint becomes an active air-purifying surface that helps protect people from harmful gases. Photocatalysis also provides for self-cleaning, anti-bacterial and de-odorizing properties.

Air cleaning paint would be of benefit in areas with high NOx levels, which would include indoor car parks, houses and buildings in urban areas.

These types of paints offer a number of advantages including:

- Air-cleaning and Self-sanitizing
- Anti-bacterial Protection properties
- Odor-less and low VOC
• Water-based, lead-free and mercury-free
• Outstanding color retention
• Low maintenance

Both cleaning paints and trees take out air pollutants like NOx from the air. A mature tree cleans 155 grams of NOx per year. It is estimated that a cleaning paint can take out up to 160 grams of NOx per square meter per year. It is easy to deduce that 1 square meter of a cleaning paint has the equivalent pollution reduction of one mature tree.

Within the realm of air cleaning paint, we find also the application of self-cleaning building surfaces, a concept learned from the liquid repellency of a surface is principally governed by a combination of its chemical nature and topographical microstructure. Self-cleaning methods currently employed are based on understanding of the functions, structures, and principles of various objects found in living nature (Nishimoto and Bhushan, 2013. Although flat low surface energy materials can often exhibit high water contact angle values, this is not normally sufficient to yield super-hydrophobicity (description reserved for materials upon which water drops move spontaneously across horizontal or near horizontal surfaces). In order for this behavior to occur, the difference between advancing and receding contact angles (hysteresis) must be minimal. Effectively, the hysteresis can be regarded as the force required to move a liquid droplet across the surface; i.e. in the case of little or no hysteresis, very little force is required to move a
droplet, hence it rolls off easily. Theoretical studies for idealized rough hydrophobic surfaces predict that contact angle hysteresis initially increases with surface roughness, until eventually a maximum value is reached; greater roughness scales beyond this lead to a fall due to the formation of a composite interface (liquid unable to completely penetrate the surface). The latter can be described by the Cassie-Baxter state, where the inherent surface roughness causes air to become trapped in voids (i.e. prevents liquid from wicking). Hence low contact angle hysteresis can be achieved by substrate roughening to produce a composite interface.

An example shown in this paper is self-cleaning concrete surfaces of a particular company which holds a patented Portland cement whereby the key properties are photocatalytic components that use the energy from ultraviolet rays to oxidize most organic and some inorganic compounds. Air pollutants that would normally result in discoloration of exposed surfaces are removed from the atmosphere by the components, and their residues are washed off by rain (Fig. 7). So, this new cement can be used to produce concrete and plaster products that save on maintenance costs while they ensure a cleaner environment.

![Fig. 7: Self-Cleaning cement application.](image-url)
2. Conclusions

Selecting a glazing technology for a window system, is critical since both static and dynamic glazing have their own problems in offering a balance between visual and energy aspects. Problems, beyond glazing properties, arise in regions with distinctive seasonal change. Climate background is also a very important key to determine the suitable glazing of buildings. They can be very effective thermally and visually, when properly selected based on the building operation, site locations and requirements.

The major drawback of the environmentally-activated windows is their inability to regulate the transition. On the other hand, electrically activated smart glazing offers the user better control over the daylighting and thermal gains into the building.

Designing a static glazing system requires more consideration of optimization when compared to a dynamic glazing technology. The qualities and performance of glazing is proportional to the cost. Dynamic glazing is more suitable in buildings like office buildings, which demand high energy performance, occupants’ comfort and productivity, in terms of daylighting and energy loads.

Air cleaning paints offer significant economic, environmental as well as health advantages, and are feasible for all exterior surfaces of buildings; particularly in urban areas due to their excellent pollution reduction properties.

References


