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Study of Thin Films to Enhance Window Performance in Buildings

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ABSTRACT

Thin film coatings can be applied to windows in existing buildings for solar control and energy-saving purposes. By controlling the entrance of solar radiation through the windows in a spectrally selective manner, it is possible to save energy in air conditioning and enhance the indoor comfort level. This research investigates the properties of thin films and their application in energy-efficient windows. The thermal, solar, visual and daylighting performance of window glass with thin films are examined. The energy and economic impacts of applying thin films are assessed through analytical and simulation methods.

It is found that the primary energy benefit of window films is limiting infrared solar heat gain. Because there are so many variables related to the characteristics and application of window films, it is essential to have the energy impact of the project analysed carefully before committing to a replacement or upgrade project. The amount of savings that will be produced by the film depends on its level of infrared reflectivity, the thermal energy properties, the exposure of the window and the climate where the building is located.

Keywords: Thin films, window films, window performance, Hong Kong.

薄膜對提高樓宇窗戶性能的研究分析

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薄膜塗層可以應用在現有樓宇的窗戶，用來達到控制太陽輻射和節能的目的。 以光譜選擇性的方式來控制通過窗戶的太陽輻射，可以節省空調耗能和提高室內舒適水平。 這項研究主要調查常見薄膜的特性和他們如何應用在節能窗戶上。 本研究審查了玻璃窗在應用薄膜後的熱量、太陽輻射、視覺和採光表現。 同時亦通過分析和模擬方法，評估其應用薄膜後的能耗和經濟影響。 研究結果發現窗戶薄膜的主要節能好處在於限制太陽光紅外線的熱能量。 由於窗戶薄膜的特徵和應用有許多變化因素，在應承替換或提昇樓宇窗戶之前，必須仔細地分析其對建築能耗之影響。 由薄膜所產生的節省能量取決於它的紅外反射性水平、熱能量特性、窗戶的曝光程度，和建築位處的氣候。

1. INTRODUCTION

Windows have a large impact on the energy performance of a building. During the last decade window technology has seen more dramatic changes and significant advances than any other building technology (Muneer, et al., 2000). The innovation in glass properties and performance attributes has made it possible for the architectural window to fulfill its role without adverse impact on building occupants and owners (Selkowitz, 1999). New window technology could improve the comfort and performance of building occupants, add value and reduce energy costs for building owners, and assist in global efforts to reduce greenhouse gas emissions that contribute to global warming (Carmody, et al., 2004).

One important window technology is thin film coatings which can be applied to window glasses for solar control and energy-saving purposes (Chaiyapinunt, et al., 2005; Correa and Almanza, 2004; Li, et al., 2004). Film coatings in glass windows of buildings have been used extensively to control the entrance of solar radiation. In warm regions, it is believed that by controlling the entrance of solar radiation through the windows in a spectrally selective manner, it is possible to use less energy in air conditioning and enhance the comfort level inside the rooms (Durrani, et al., 2004). For existing buildings, in particular, many of the solar control benefits of tinted, reflective and low-e (low-emissivity) glass are available by applying window films to existing windows.

This research investigates the properties of thin films and their application in energy-efficient windows. The thermal, solar, visual and daylighting performance of window glass with thin films are examined. The energy and economic impacts of applying thin films are assessed through analytical and simulation methods. It is hoped that better understanding about the application of thin films to windows can be developed for promoting energy efficiency in buildings.

2. THIN FILM TECHNOLOGY

Thin film coatings refer to single or multiple layer of metals or semiconductors being applied to the inner surface of architectural windows. These window films can offer solar control functions to reduce the cooling costs and improve comfort level in buildings (Al-Kuhaili, 2004; Chaiyapinunt, et al., 2005; Correa and Almanza, 2004). Nowadays, advanced engineering techniques are often used to deposit micro-thin layers of metal alloys to give window films their energy control and other properties (Russo, et al., 2001). Certain combination films are designed to deliver two or more performance properties simultaneously, such as solar protection, visibility, safety from broken glass and fade reduction of fabrics (Smith, Ben-David and Swift, 2001).

For solar control or protection purpose, window films are typically thin layers of polyester film that can either be clear, tinted or reflective. The principal function is to reflect back the worst of the suns heat and glare. These films can reduce solar heat gain by as much as two thirds, and some films will provide good solar control while allowing good visible light transmission. An extensive range of tinted and reflective films offers a wide choice of performance properties, together with aesthetic options. Some films also use thin coatings similar to those used in low-e windows. In addition, some solar control window films can provide effective electromagnetic radiation shielding too.

Table 1 presents some examples of the performance characteristics of window films applied to clear glass. Different window films perform differently. It is important to compare their properties, including emissivity, shading coefficient (SC), solar heat gain coefficient (SHGC) and visible light transmission (VLT). In general, lower emissivity films are best for year-round comfort and savings. Lower SC films block more heat. Lower VLT films block more glare, but can make the window darker.

Table 1: Example performance of clear glass with and without window films

Type of window glazing	Shading coefficient	Solar heat gain coefficient	Visible light transmittance
Single-pane 6 mm glazing			
- Clear glass (base case)	1.00	0.86	90%
- Clear with tinted film	0.50	0.43	48%
- Clear with reflective film	0.29	0.25	15%
- Clear with spectrally selective film	0.51	0.44	69%
Double-pane 6 mm glazing			
- Clear glass (base case)	0.87	0.75	81%
- Clear with tinted film	0.56	0.48	43%
- Clear with reflective film	0.42	0.36	16%
- Clear with spectrally selective film	0.58	0.50	62%

Early generation films could easily be damaged or develop bubbles. Today's films offer better adhesion and resist surface damage. Significant advances in quality control, production speed, and reproducibility of window films have dropped the cost of sophisticated multilayer coatings significantly, thus enhancing their economic attractiveness. However, the films still have a service life that is less than that of the window to which they are applied. Most manufacturers offer guarantees that the film will last for at least five years. This means that it will be necessary to replace the film sooner than the windows and that careful analysis of the life cycle economics is important.

3. WINDOW PERFORMANCE

Windows have always been an essential element in building design (Muneer, et al., 2000). They provide the building façade with a distinguishing appearance from the outside of the building, and help to define the nature of indoor spaces, by providing natural daylight with variable quantity and quality over time and weather (Selkowitz, 1999). From the building owner's perspective, better windows keep the natural elements at bay and help to reduce annual energy costs. From the occupants' perspective, daylight in the building enhances the quality of most indoor spaces, and the view and connection with the outdoors provides essential amenity for offices or factories.

The performance of windows can be evaluated by looking at two major aspects:

- Thermal and solar performance
- Visual performance and daylighting

3.1 Thermal and Solar Performance

There are many factors which affect the thermal performance of windows. The local climate, the framing material, the window construction and the quality of installation will all affect the performance of the total window. Since glass represents up to 85 percent of any window, the quality and properties of that glass are extremely important in measuring overall window performance. Figure 1 shows the typical transmission properties of windows, including transmittance, reflectance and absorptance (Environmental Advisory Service, 1988).

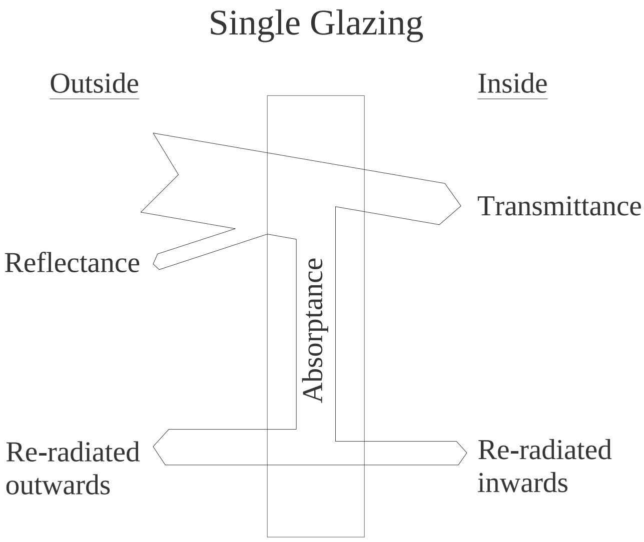

Figure 1. Transmission properties of windows

Thermal transmission through a window is typically 10 to 20 times as great as through exterior walls, thus increasing the load on the building's air conditioning and heating systems. The infrared portion of sunlight significantly increases cooling loads. In buildings with large areas of glass, infrared energy can heat perimeter areas enough to make them uncomfortable, even during winter months.

The role of windows regarding the cooling and heating of buildings is especially essential in the perimeter zones. Because windows modulate heat, light and fresh air, they have an important influence on the energy use and well-being of people in the perimeter zone, even if it is a small percentage of the total building floor area. Thermal impacts due to cold or hot window surfaces will directly affect thermal comfort of occupants close to the exterior walls.

Generally speaking, the thermal performance of windows can be improved by minimising solar heat gain in cooling-dominated climates and by minimising heat loss in heating-dominated climates. Thus, windows with lower SHGC perform better in cooling-dominated climates, and windows with lower U-values perform better in heating-dominated climates.

Moreover, adequate window shading is critical in hot climates and the solar performance of windows with shading devices (interior or exterior) shall be considered carefully. If properly designed, shading for windows can reduce cooling costs and increase comfort while providing pleasant ambient daylighting. If window films are also applied, then the combined sun control effect would normally be reduced since the shaded window area will receive less solar radiation.

3.2 Visual Performance and Daylighting

Since cooling requirements dominate the building energy consumption and indoor comfort conditions in hot and humid climates, like in Hong Kong, window selection is a process of maximising daylighting while minimising summer heat gain (Li, et al., 2004). Proper consideration of visual comfort performance and daylighting strategies is needed. Spectrally selective glazing is often used to achieve this objective.

By controlling solar heat gains in summer, preventing loss of interior heat in winter, and allowing occupants to reduce electric lighting use by making maximum use of daylight, spectrally selective glazing can significantly reduce building energy consumption and peak demand (Selkowitz, 1999). Figure 2 shows a comparison of visual performance of two types of thin films. It can be seen that the VLT has a direct impact on the view provided by the window and the availability of daylight.

Figure 2. Comparison of visual performance for two types of thin films

Spectrally selective glazings are designed specifically to admit a higher level of visible light while still controlling solar heat. They do so by responding differently to different wavelengths of solar energy allowing for much clearer glass with good solar control. With a virtually clear appearance, they admit more daylight and permit much brighter, more open views to the outside while still providing much of the solar control of the dark, reflective energy-efficient glass. They can also be combined with other absorbing and reflecting glazings to provide a whole range of sun control performance.

In fact, popular “low-e” glazings are a type of spectrally selective glazing that is typically selected to provide enhanced insulation value, good VLT and good solar control. Some low-e windows, however, can allow more solar heat to penetrate than others so it is important to evaluate glazing options against a project’s design criteria. Basically, low-e coating are microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window glazing surface primarily to reduce the U-value by suppressing radiative heat flow.

The principal mechanism of heat transfer in multi-layer glazing is thermal radiation from a warm pane of glass to a cooler pane. Coating a glass surface with a low-e material and facing that coating into the gap between the glass layers blocks a significant amount of this radiant heat transfer, thus lowering the total heat flow through the window. Different types of low-e coatings have been designed to allow for high, moderate or low solar gain. At present, low-e window films are more expensive than normal window films, but they are becoming more and more popular in the market because of their good energy-saving/comfort properties.

4. ANALYSIS OF ENERGY AND ECONOMIC IMPACTS

The amount of radiant solar energy that enters a building depends on the type of glazing, any surface treatments of the glass, the window's orientation and exterior or interior shading. For all of these reasons, cooling load reduction and energy savings will vary significantly depending on the specific application. In general, clear east and west windows will gain the most heat in the summer. In the winter, the south windows will gain the most. If a building has unshaded clear glazing on the east, west or south sides, then adding window film will most likely result in considerable energy savings.

To take advantage of natural daylight, it is necessary to use film that allows plenty of natural light to enter (high VLT). For reducing cooling costs, priority should be given to west or east facing windows. South facing windows are the second priority. North windows are the lowest priority from an energy and comfort point of view, although it may be necessary to include north windows in a window film retrofit for aesthetic and appearance reasons.

In our research study, investigations have been carried out to analyse the energy impacts of applying different thin films to different types of window glass, under the climatic conditions in Hong Kong. Evaluation has been made on the effects of daylighting controls. Cost benefit analysis has also been performed for some typical buildings with the aim to understand the economic factors and technical requirements in window film applications. In addition, the do-it-yourself (DIY) method of applying window films is discussed.

4.1 Thin Films Applied to Different Window Glass

Different types of window films are available from manufacturers that can meet a wide range of solar control and visible light design criteria. In our study, we have selected 6 types of window films to represent those films commonly used in existing buildings. Table 2 shows the properties of the thin films being evaluated (CG-1 to CG-6; CG-0 is a clear glass).

Table 2: Properties of the thin films being evaluated

Thin Film Test Name	Solar Energy			Visible Light			Emissivity	Thermal Energy		
	% Transmittance	% Absorptance	% Reflectance	% Transmittance	% Absorptance	% Reflectance		"U"-value ($W/m^2/^oC$)	Shading Coefficient	Solar Heat Gain Coefficient
CG-0*	83	9	8	90	2	8	0.84	6.3	1	0.86
CG-1	59	32	9	64	25	11	0.89	6.42	0.79	0.68
CG-2	44	44	12	48	39	13	0.89	6.42	0.66	0.57
CG-3	39	48	13	42	43	15	0.88	6.42	0.61	0.52
CG-4	31	52	17	34	46	20	0.86	6.36	0.53	0.46
CG-5	22	55	23	23	49	28	0.84	6.3	0.43	0.37
CG-6	9	55	36	9	48	43	0.79	6.13	0.28	0.24

To investigate the energy impacts of these films on different types of window glasses, a series of computer modelling and simulation have been carried out using the energy simulation software "Energy-10" (Balcomb, 2004). Base case models were developed for three types of buildings in Hong Kong, namely, office, hotel and residential building. Typical weather year for Hong Kong was used in the simulation. Five types of existing windows were considered, including clear glass, tinted glass, reflected glass, double-glazing and low-e glass. The purpose is to study the relative effect of window films on annual building energy consumption.

Figure 3 presents the simulation results for the effects of thin films on different types of window glasses in the office building. It can be seen that the energy saving is most obvious in the case of clear glass, whereas for low-e glass, the energy saving is relatively small because the solar control is already quite effective.

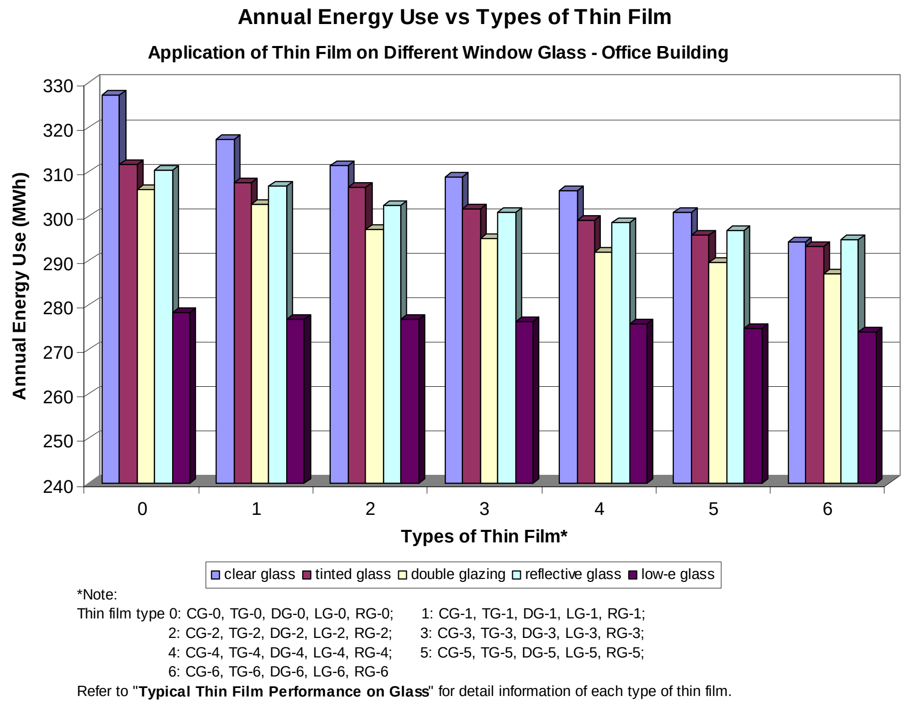

Figure 3. Effects of thin films on different types of window glasses

4.2 Effects of Daylighting Controls

To study how daylighting controls may affect the overall impact of window films, computer simulations were carried out using the same office building model, but with addition of two daylighting control methods, namely, continuous dimming and 3-step dimming. It should be noted that the Energy-10 software only has a simple algorithm to model daylighting design and could not consider every details of the system. Nevertheless, the simulations can provide an indication to assess the effects of daylighting controls. Figure 4 shows the effects of thin films on clear glass with the daylighting controls. In this case the two daylighting control methods give similar results, with continuous dimming slightly lower in annual energy use. When comparing the results for clear glass in Figure 3, it can be seen that daylighting controls produce significant energy savings for the window systems.

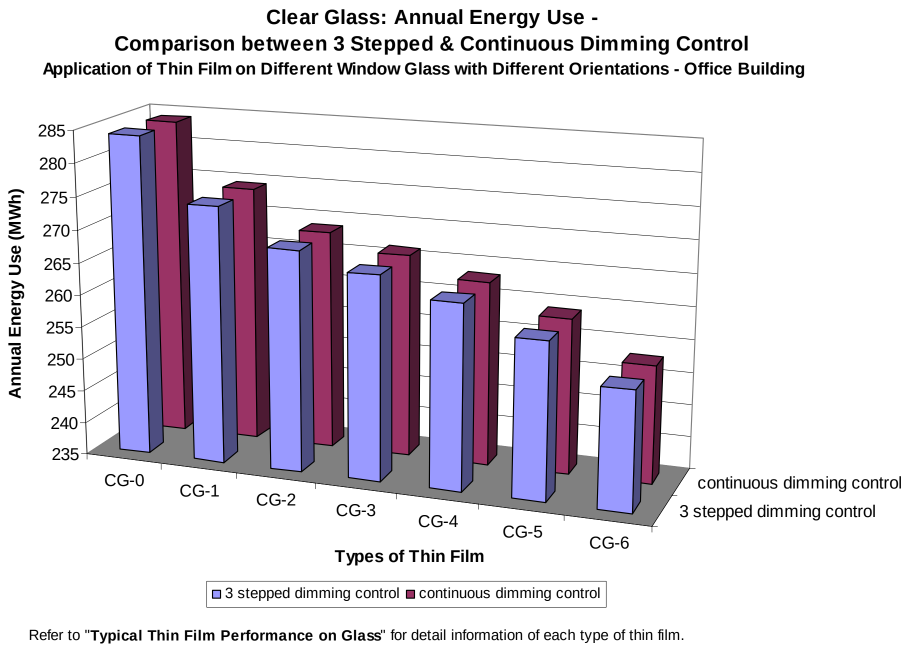

Figure 4. Effects of thin films on clear glass with daylighting controls

4.3 Cost Benefit Analysis

In order to evaluate the economic justification of window film retrofit, the cost components and benefits of typical window film projects are studied and analysed. The basic cost components considered include installation costs (material and labour costs), energy costs and maintenance costs. To assess the attractiveness of applying different types of films to different types of windows, simple payback periods were determined and shown in Figure 5.

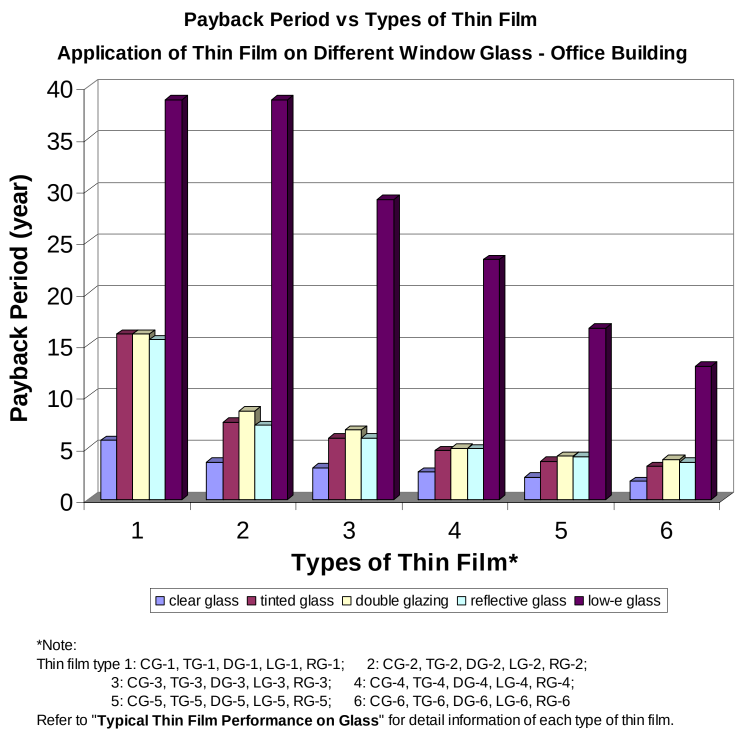

Figure 5. Comparison of simple payback periods for different types of thin films

It can be seen from Figure 5 that for the office building case, clear glass applications provide payback periods in the range of 2-5 years. Tinted and reflective glass applications give payback periods about 3-15 years. Low-e glass applications, which are already energy efficient, have very long payback periods of about 12-38 years. It should be noted that after the initial screening with simple paybacks, life cycle analysis shall be used to evaluate the available options and identify the most effective one for recommendation.

When the amount of energy saved is being studied in practical projects, usually only the thermal energy (SC and SHGC) is taken into account because the estimation of daylighting and other behavioural effects is difficult to manage accurately. In fact, without the intense radiant heat and glare from windows, people can be very comfortable with the thermostat set several degrees higher in the summer. This can result in up to a 10 percent electricity savings.

4.4 Do-It-Yourself for Window Films

On the other hand, for residential buildings, it was found that the economic analysis would be very different if building owners choose the do-it-yourself (DIY) method of applying window films. Actually, the window film is available in rolls or single window boxes for DIY application (often come with a simple installation kit) or from professional installers. Installing the film through DIY method can save up to 75 percent of the cost of professionally installed film. In societies where labour cost is high, like Hong Kong, this option is very attractive. Usually, the primary difference between DIY and professional films from companies that offer both is the type of adhesive used. On all but the largest windows which require more installation skills, DIY application looks as good. One advantage of professional installation is a long warranty, however, the project has to meet a minimum amount or scale in order to be economical.

The residential market represents good potential for window film application because there is a trend for larger and larger window area in our residential buildings. In principle, residential window films are considered permanent because, with proper cleaning, they can last ten years or more (Carmody, et al., 2000). If the building owners decide to remove the film at a later date, the manufacturers could offer removal solutions that quickly dissolve the adhesive. The window glass surface is not harmed since most films have a water-activated adhesive on one side.

Similarly, for some hotel buildings, if they have their own manpower and time available for applying the window films, then the labour cost will be reduced significantly by using the “DIY” approach. Standardisation of the sizes of window films for hotel guestrooms also enhance the economy of scale. Remember, if you can wash a window, then you can easily install a window film kit yourself for your building.

5. CONCLUSIONS

Solar control thin film applied to existing windows will reduce thermal conduction slightly, but the primary energy benefit is limiting infrared solar heat gain. These reductions will reduce energy costs and enhance thermal comfort in many buildings. Because there are so many variables related to the characteristics and application of window films, it is essential to have the energy impact of the project analysed carefully before committing to a replacement or upgrade project. Evaluating different options will also allow building owners to select the windows that are best suited for their particular application. Failure to do so will result in unrealistic energy savings expectations.

At present, some unrealistic claims for solar control window films can be found in the market. In fact, the amount of savings that will be produced by the film depends on its level of infrared reflectivity, the thermal energy properties, the exposure of the window and the climate where the building is located. Again, before committing to a window film project, it is necessary to have the energy impact analysed for the facility and not to project the savings based on some generalised application.

The results from this research study could provide useful information and data on the technical considerations, energy and economic impacts, and practical design issues that drive window film and design decisions. Hopefully, this will help to develop better understanding about the window film application and their contribution to better, sustainable buildings.

REFERENCES

Al-Kuhaili, M. F., 2004. Optical properties of hafnium oxide thin films and their application in energy-efficient windows, *Optical Materials*, 27 (3): 383-387.

Balcomb, J. D., 2004. *Mastering Energy-10*, National Renewable Energy Laboratory, Golden, CO.

Carmody, J., et al., 2004. *Window Systems for High-performance Buildings*, Norton, New York.

Carmody, J., et al., 2000. *Residential Windows: A Guide to New Technologies and Energy Performance*, 2nd ed., Norton, New York.

Chaiyapinunt, S., Phueakphongsuriya, B., Mongkornsaksit, K. and Khomporn, N., 2005. Performance rating of glass windows and glass windows with films in aspect of thermal comfort and heat transmission, *Energy and Buildings*, 37 (7): 725-738.

Correa, G. and Almanza, R., 2004. Copper based thin films to improve glazing for energy-savings in buildings, *Solar Energy*, 76 (1-3): 111-115.

Durrani, S. M. A., et al., 2004. Dielectric/Ag/dielectric coated energy-efficient glass windows for warm climates, *Energy and Buildings*, 36 (9): 891-898.

Environmental Advisory Service, 1988. *Glass and Transmission Properties of Windows*, Pilkington Glass Limited, England.

Li, D. H. W., et al., 2004. Lighting and energy performance of solar film coating in air-conditioned cellular offices, *Renewable Energy*, 29 (6): 921-937.

Muneer, T., et al., 2000. *Windows in Buildings: Thermal, Acoustic, Visual, and Solar Performance,* Architectural Press, Oxford, U.K.

Russo, D., et al., 2001. The influence of film composition on the optical and thermal properties of solar control coatings, *Thin Solid Films*, 398-399 (2001): 65-70.

Smith, G. B., Ben-David, A. and Swift, P. D., 2001. A new type of TiN coating combining broad band visible transparency and solar control, *Renewable Energy*, 22 (1-3): 79-84.

Selkowitz, S. E., 1999. High performance glazing systems: architectural opportunities for the 21st century, In *Proceedings of Glass Processing Days Conference*, Tampere, Finland, June 13-16, 1999, LBNL-42724: WG-411.