doi:10.4186/ej.2009.13.1.29

SELECTING GLASS WINDOW WITH FILM FOR BUILDINGS IN A HOT CLIMATE

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ABSTRACT

This article is about the developing parameters and relationships for selecting a proper glass window applied with film as building envelopes for buildings located in a hot climate based on its thermal performances. Thermal comfort of the occupants sitting near the glass window is the thermal performance that needed to be considered besides the heat transmission in selecting a proper type of glass to use as a glass window for the building. The predicted percentage of dissatisfied (PPD) is chosen as a thermal comfort index. 45 types of film and 1280 glass windows with film are investigated in this study. It can be shown that the thermal comfort index is dependent on the optical properties (total transmittance and total absorptance) and the overall heat transfer coefficient of glass windows with film. Glass window with film which has high transmittance shall have more discomfort due to solar radiation effect. Glass window with film which has high absorptance shall have more discomfort due to surface temperature effect. The discomfort from the surface temperature effect for double pane glass window with film is also dependent on the glass thickness other than the absorptance and the change in overall heat transfer coefficient. Expressions for predicting the performance of the glass windows with film in terms of thermal comfort are developed.

KEYWORDS

glass windows; thermal comfort; predicted percentage of dissatisfied; a hot climate.

doi:10.4186/ej.2009.13.1.29

I. Introduction

Glass windows are common building envelopes used in many large office and commercial buildings in Thailand. Glass windows are installed as a physical and visual connection to outsiders as well as to make the appearance of buildings look more aesthetically pleasing. For a country located in the tropical zone (hot climate) like Thailand, glass windows installed in buildings also act as a means of admitting large amounts of solar radiation into buildings and converting it into building heat gain. This heat gain is then converted into building cooling load. Many countries in this tropical zone (i.e. Thailand, Singapore, Hong Kong, etc.) have issued energy conservation laws ([1], [2] , [3], etc.) to control energy usage in buildings. These laws usually limit the amount of heat gain passing through the building envelope. Problems may arise when the existing buildings have values of heat gain through the building envelope (usually the glass windows) exceeding the regulation values. Besides changing the existing glass window to a better thermal performance glass, applied film to the glass window has become the easiest way to change building envelope properties in reducing the heat gain through the envelope to the regulation values. Data of film properties available for customer in Thailand are usually given in the form of overall values (not in function of wavelength) and the values given are usually referenced to clear glass. But glass used for glass windows in existing buildings can be of various types, such as, clear glass, tinted glass and reflective glass, etc. Therefore, when anyone wants to change glass window properties to reduce heat transmission by applying film to the glass window which is not a clear glass, he should not directly use the given film properties based on clear glass in the overall value in any analyses. The spectral optical properties of the individual glass and film are needed in order to find the combined spectral optical properties of the glass with film.

The heat transmission through the glass window consists of the heat transmission in the conduction/convection mode and the radiation mode. The portion of the incident solar radiation on the glass window enters the room dependent on the glass window's optical properties (transmittance and absorptance). The transmitted radiation becomes instantaneous room heat gain while the absorbed radiation in the glass window becomes the delayed heat gain (sometime called heat gain from the longwave radiation). The absorbed radiation will cause the glass temperature increased and the heat will then be reradiated into the room from the higher glass surface temperature to the lower room air temperature. Glass window affects the building not only in terms of heat transmission but also in terms of thermal comfort. Most people emphasize the issue of energy conservation in buildings by concentrated on reducing heat transmission through the building envelope. Applied film to the glass window can cause the value of total transmittance of the glass window with film reduced (which results in reducing heat transfer through glass window) but it also causes the value of the total absorptance of the glass window with film increased. The high absorptance of the glass window with film will make its surface temperature increased. The reradiated heat due to the high surface temperature could cause the people who stay close to the window feel uncomfortable though the value of the heat transmission through the glass window with film is reduced. Most of the time people tend to lower the temperature set point of the air conditioning system to compensate this uncomfortable condition which resulted in using more energy than necessary. Therefore a thorough understanding of the thermal performance of the building's glass windows and glass window with films both from the aspect of heat transmission and thermal comfort is essential for design architects, design engineers and building owners. Chaiyapinunt et al. [4] have previously done some work on the thermal performance rating of the glass windows and glass windows with film under local design conditions in respect with heat transmission and thermal comfort. Singh et al. [5] have also studied the impact of different glazing systems on human thermal comfort in Indian scenario. In the previous work of [4], the predicted percentage of dissatisfied (PPD) and the relative heat gain (RHG) were chosen as the thermal comfort index and heat transmission index, respectively. Certain relationships between the thermal comfort index and the total optical properties of the glass windows and glass window with films, transmittance and absorptance, were developed. But only 4 types of film were studied then. In this article, the more comprehensive work on the effect of films applied on the glass window in aspects of human thermal comfort is investigated.

II. Thermal performance and heat transmission indices and design condition

Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment (ISO 7730 [6] and ASHRAE Standard 55 [7]). The predicted percentage of dissatisfied (PPD) is chosen as the thermal comfort index in this study. PPD index is defined as the index predicting the mean response of a large group of people who will not be satisfied with the thermal environment they occupied. The other related thermal comfort index is the predicted mean vote (PMV) index. PMV index is defined as the index predicting the mean response of a large group of people to thermal environment. The index is classified as seven levels between +3(hot) and -3(cold) which level 0 is neutral. The values of PMV range of ± 0.5 which corresponding to the PPD value of 10% are usually accounted as acceptable condition. Fanger [8] related predicted mean vote (PMV) value to the parameters that affect thermal comfort and also related the PPD value to the PMV value by the following equations:

$$\begin{aligned} PMV = &\left(0.352e^{-0.042 \cdot M} + 0.032\right) \cdot [M(1-\eta) - 0.35 \cdot (43 - 0.061 \cdot M(1-\eta) - P_a) - 0.42 \cdot (M(1-\eta) - 50) \\ &- 0.0023 \cdot M \cdot (44 - P_a) - 0.0014 \cdot M \cdot (34 - T_a) - 3.4 \times 10^{-8} f_{cl} \cdot ((T_{cl} + 273)^4 - (T_{mrt} + 273)^4) \\ &- f_{cl} \cdot h_c (T_{cl} - T_a)] \end{aligned} \quad (1)$$

$$PPD = 100 - 95 \cdot e^{-(0.03353 PMV^4 + 0.2179 PMV^2)} \quad (2)$$

where
M = metabolic rate per unit body, kcal/(hr-m^2)
P_a = vapor partial pressure, mm Hg
f_{cl} = clothing area factor
T_{mrt} = mean radiant temperature, °C
T_a = air temperature, °C
T_{cl} = clothing surface temperature, °C
h_c = convective heat transfer coefficient, kcal/(hr-m^2)
η = mechanical efficiency

Unfortunately the expression of PMV using mean radiant temperature that does not account for solar radiation in equation 1 cannot be used for calculating PMV that includes the effect of solar radiation striking on the person in the enclosure. Therefore, in order to take into account the effect of solar radiation exposed to a person, there shall be two mean radiant temperatures in this study. The first is the mean radiant temperature of the enclosure that does not account for solar radiation (sometimes called unirradiated mean radiant temperature). This mean radiant temperature is mainly dominated by glass surface temperature. The second mean radiant temperature is the total mean radiant temperature that accounts for the effect from surface temperature and radiation that the person in the enclosure is exposed to. Such mean radiant temperatures as suggested by Fanger [8] can be written as

$$T_{tmrt} = [(t_{s1} + 273)^4 \cdot F_{p-1} + (t_{s2} + 273)^4 \cdot F_{p-2} + ... + (t_{sn} + 273)^4 \cdot F_{p-n}]^{0.25} - 273^\circ C \quad (3)$$

$$T_{smrt} = \left[(T_{tmrt} + 273)^4 + f_p \cdot a_k \cdot \frac{q}{\varepsilon_p \cdot \sigma} \right]^{0.25} - 273 \quad (4)$$

where
T_{tmrt} = mean radiant temperature due to surface temperature, °C
T_{smrt} = mean radiant temperature due to surface temperature and solar radiation, °C
t_{sj} = surface temperature of the enclosure wall number j, °C
$F_{p\text{-}j}$ = angle factor between the person and surface i $(\sum_j^n F_{p-j} = 1)$
f_p = projected area factor
a_k = absorptance of the outer surface of the person (standard value = 0.6)
ε_p = emittance of the outer surface of the person (standard value = 0.97)
σ = Stefan Boltzmann constant, W/m^2-K^4
q = solar radiation intensity passing through the glass window that the person in the enclosure exposed to, W/m^2

The solar radiation passing through the glass window q can be determined by the following relation as

$$q = I_{dirv} \cdot T(\theta) + I_{diffv} \cdot T_{herm} \quad (5)$$

where I_{dirv} = direct solar radiation striking on the vertical glass surface (W/m^2)
I_{diffv} = diffuse solar radiation striking on the vertical glass surface (W/m^2)
$T(\theta)$ = glass transmittance which is dependent on incident angle
T_{herm} = hemisphere glass transmittance

As previously stated, equation 1 can be used to calculate only for the PMV that does not account for the solar radiation effect (PMVno solar), the PMV which also accounts for the solar radiation effect shall be calculated by using the relation suggested by Lyons [9] and Sullivan [10] as

$$\frac{dPMV}{dq} = \frac{\partial PMV}{\partial T_{mrt}} \cdot \frac{\partial T_{mrt}}{\partial (a_k f_p q)} \cdot \frac{\partial (a_k f_p q)}{\partial q} \tag{6}$$

$$PMV = PMV_{no\,solar} + \frac{dPMV}{dq} \cdot q \tag{7}$$

PPD values that account for the solar radiation effect and surface temperature effect can be calculated from equation 2 by using PMV values obtained from equation 7. Then the value of PPD due to solar radiation effect (PPDsolar) can be obtained by subtracting the PPD value due to the surface temperature effect (PPDsurface temp) from total PPD value (PPDtotal) according to the relationship shown in equation 8.

$$PPD_{total} = PPD_{surface\ temp} + PPD_{solar} \tag{8}$$

The glass window surface temperature and overall heat transfer coefficient can be calculated by using the method suggested by Finlayson et al. [11]. The calculation is done by balancing the heat flux of each layer of glass and environment.

The validation of the mathematical models for thermal comfort index was carried out in Chaiyapinunt et al. [4].

For this study, the outside design condition was chosen based on 12 years (1988-1999) of Bangkok weather data collected by the meteorological department to represent a local design weather condition of a hot climate. The selection is done based on considering the most influential parameters on the thermal performance of the glass windows and glass windows with film. The parameter chosen is the solar radiation. The 0.4% annual cumulative frequency of occurrence for global radiation as suggested by ASHRAE [12] is selected. The outside design condition was then chosen as

- Direct normal solar radiation on glass windows and glass windows with film = 658 W/m^2
- Diffuse solar radiation on glass windows and glass windows with film = 111 W/m^2
- Outside air dry bulb temperature = 35 °C
- Outside wind velocity = 3.8 m/s

The room that was used in the mathematical model to calculate the thermal performance of the glass windows with film for the study is 4 meters by 4 meters and 3 meters in height with one external wall and three internal partitions. Glass windows with film are installed in the whole area of the external wall, facing west. The person in this study sits turning sideways to the glass window at a distance of 1 meter. The typical working conditions for an office in Bangkok are chosen as the design condition. The inside design condition in this study is then chosen as

- Inside air dry bulb temperature = 25 °C
- Inside air velocity = 0.15 m/s
- Relative humidity = 50 %
- Clothing insulation = 0.5 clo.
- Metabolic rate for activity = 1.2 met (1 met = 58 W/m^2)

doi:10.4186/ej.2009.13.1.29

III. Glass window and films

Glass windows that are commonly used in buildings can be classified as single pane glass and double pane glass. Glass is also classified according to the type as clear, tinted, reflective and low-e glass. Clear glass and tinted glass are usually referred to the same group according to the manufacturing method. Reflective, low-e and glass applied with film are usually referred to another group. Reflective glass is a clear or tinted glass coated with thin metallic film by using a sputtering technique. Low-e glass is a double pane clear glass or tinted glass with a low emissivity coating on the inner surface of the outer pane glass. Therefore reflective glass and low-e glass are usually defined as special types of glass applied with film. Each type of glass has unique spectral optical properties which varied with the wavelength. The solar radiation has spectral range from about 0.38 to 3.5 µm. The range of wavelength of the solar radiation spectrum is divided into the visible range (0.38-0.76 µm) and the infrared range (0.76-3.5 µm). The spectral optical properties are dependent on the type and thickness of the glass. The spectral optical properties of glass, the transmittance, absorptance and reflectance, are the main properties that affect on the thermal performance of the glass windows. Since the summation of the three properties (transmittance, absorptance and reflectance) is equal to one. One property of glass will affect the other two (i.e. glass with high transmittance will have low absorptance and reflectance). The normal incidence spectral transmittance of clear glass and tinted glass are shown in Figures 1 and 2 as examples to illustrate the effect of glass type and thickness on the spectral optical properties. Figure 1 shows the normal incidence spectral transmittance of clear glass of different thickness. The effect of glass thickness on the transmittance is clearly seen in the infrared range, the thicker the glass the less transmittance value it shall have, while the glass thickness has less effect on the transmittance in the visible range. Figure 2 shows the normal incidence spectral transmittance of clear glass and tinted glass of 6 mm thickness. The effect of color in the tinted glass on the transmittance is shown in Figure 2. It is found that tinted glasses have lower spectral transmittance values for the whole spectrum ranges considered compared to the clear glass of the same thickness.

Film is a substance that design for applying to the glass to change the glass optical properties. The spectral optical properties of glass window applied with film of different types can be obtained by combining the spectral optical properties of individual glass and film using the method suggested by Rubin et al.[13]. Then the total optical properties of the glass windows with film could be obtained by integrating the product of the spectral properties and the spectral irradiance over the assigned wavelength range (0.32 – 2.5 micron is chosen to be limit of integration) and weighting it with the result from the integration of the spectral irradiance itself over the same assigned wavelength range.

Most of the films available in the market are listed in the OPTIC5 library [14] . In this study, 45 types of film (all of the available films from OPTIC5 library) are chosen. They are grouped into 6 groups according to the pattern of the spectral transmittance and reflectance. For films in group A, the pattern of the spectral transmittance in the visible range (0.38-0.76 µm) is similar to the spectral transmittance in the infrared range (0.76-3.5 µm). There are 12 types of film that fall into group A. For films in group B, the spectral transmittance in the visible range is larger than the spectral transmittance in the infrared range. There are 16 types of film that fall into group B. For films in group C, the pattern of the spectral transmittance in the visible range has a peak value at the beginning of the range and then decreasing values towards the end of the range. The pattern of spectral transmittance in the infrared range is similar to the one in the visible range. There are 3 types of film that fall into group C. For films in group D, the pattern of the spectral transmittance has a peak value at the beginning of the visible range and then decreasing values towards the end of the infrared range. There are 3 types of film that fall into group D. For films in group E, the values of spectral transmittance and reflectance in the infrared range are about the same as the values in the visible range. There are 6 types of film that fall into group E. For films in group F, the spectral transmittance has a small value in the visible range and has a very high value (0.8-0.9) in the infrared range. There are 5 types of film that fall into group F. Table 1 shows a list of films group A to F according to the names assigned in OPTIC5. Figure 3 shows an example of the spectral optical properties of 6 groups of film.

By considering the pattern of spectral optical properties for the films chosen, it is found that the films in group F are not suitable for commonly used in a hot climate. The films in group F when applied to the glass window will admit more heat through the window (which is not a preferred condition for building located in a hot climate) while cutting out some light. Therefore by neglecting films in group F, 40 types of film that are suitable for use in hot

doi:10.4186/ej.2009.13.1.29

climates are chosen for this study. These films are applied to the inside glass surface (surface that is facing into the room) 34 Engineering Journal of clear glass and tinted glass (green, grey and bronze glass) of different thicknesses creating 640 types of single pane glass window with film and also creating another640 types of double pane glass window with film. Figure 4 shows an example of the spectral optical properties of the single pane clear glass applied with films of different groups.

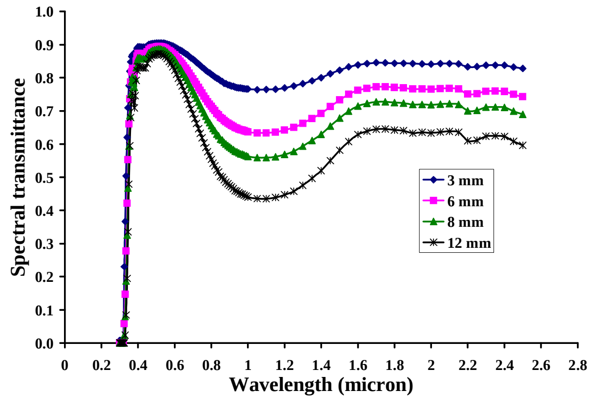


Figure 1
The comparison of the normal incidence spectral transmittance of clear glass for different thickness.

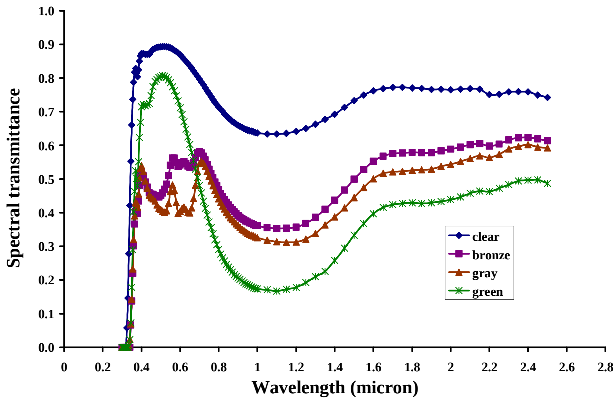


Figure 2
Normal incidence spectral transmittance of clear glass and tinted glass with 6 mm thickness.

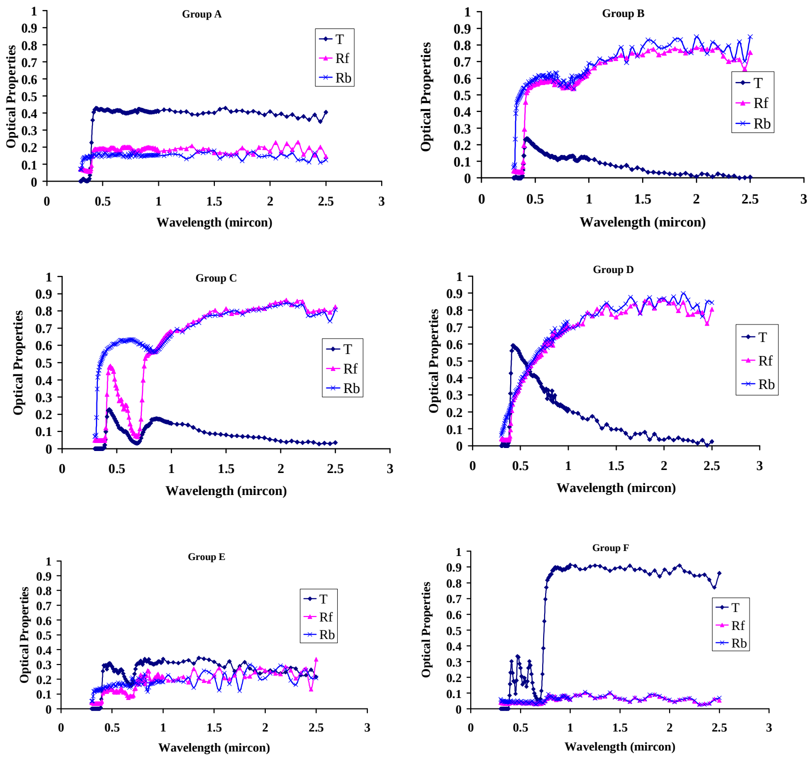
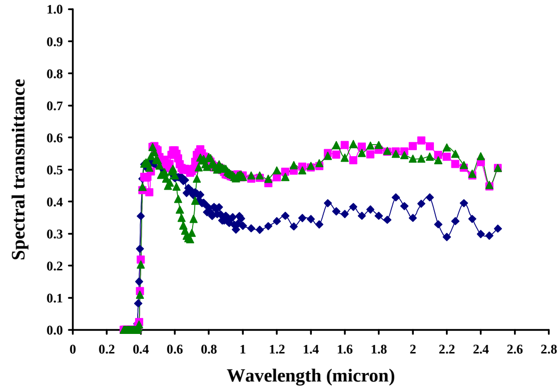


Figure 3
Example of the spectral transmittance (T), front spectral reflectance (Rf), and back spectral reflectance (Rb) of the 6 groups of film.

doi:10.4186/ej.2009.13.1.29

Figure 4
Normal incidence spectral transmittance of clear glass and tinted glass with 6 mm thickness.



IV. Performance of glass window with films

With the known optical property data of the glass window with films, their thermal properties, such as overall heat transfer coefficient, shading coefficient, solar heat gain coefficient and glass surface temperature that are based on Thailand design weather conditions, are calculated by using the method suggested by Finlayson et al. [11]. Then, with the calculated glass surface temperature, the mean radiant temperature due to surface temperature and total mean radiant temperature can be calculated. The thermal comfort index (PPD) is then calculated.

Since there are about 1,280 glass windows with film to be analyzed, only certain typical results from the analysis are shown in this article. The results of the analysis for some typical selective glass window with films of 6 mm thickness are shown in figure 5. The PPD of the same single pane and double pane selective glasses that are not applied with films along with reflective glasses are also shown in figure 5 for comparison. From figure 5, one can see that most of the glass (without films applied) with the exception of the reflective glasses have a value of PPD due to solar radiation effect greater than the value of PPD due to surface temperature effect. For single pane glass, clear glass has the highest value of total PPD. For double pane glass, clear glass also has the highest value of total PPD. This means that people who sit near clear glass windows will experience high discomfort due to direct solar beam striking them more than discomfort caused by the effect of high surface temperature. It is found that people sitting near tinted glass windows (green, grey and bronze glass) will feel a lesser discomfort effect compared to the case of clear glass windows. This is due to the difference in the optical properties of clear glass and tinted glasses. Though the PPD due to the solar radiation effect of the tinted glass is reduced but the PPD due to the surface temperature effect is increased due to the high absorptance of tinted glass. Only single pane and double pane reflective glass chosen, which have greater values in reflectance and absorptance than transmittance, have the value of PPD due to surface temperature effect greater than the value of PPD due to solar radiation effect.

Applying film to the glass window usually causes the total transmittance of the glass window with film to reduce and cause the total absorptance of the glass window with film to increase. When selected films from groups A, B, C, D and E are applied to the single pane clear glass and single pane tinted glass (bronze glass, in this case), one can see from figure 5 that the total discomfort effect is reduced compared to the case of plain glass of the same kind. It is found that, for the glass window with film, the PPD due to solar radiation effect is reduced while the PPD due to surface temperature effect is increased compared to the plain glass. The amount of the reduced value of PPD due to the solar radiation effect and the amount of the increased value of PPD due to the surface temperature effect compared to the plain glass are dependent on the optical properties of certain glass window with film. In this case film type C gives the greatest reduction in total discomfort compared to other types of film considered. Therefore it can be generally said that applying film to glass windows will reduce the discomfort due to the solar radiation effect but increase the discomfort from the surface temperature effect.

When applying film to double pane glass window (3, 6, 8 and 12 mm thickness with 6 mm air gap), it is found that the value of PPD due to surface temperature effect is increased significantly compared to plain glass window of the same kind. Therefore though the discomfort due to solar radiation effect is reduced but the total discomfort of the double pane glass window with film might not be necessarily reduced because of the significant increasing in discomfort due to the surface temperature effect. From figure 5, it is found that applying film to double pane clear glass window causes the total PPD to be decreased compared to the total PPD of the plain double pane clear glass window. But when films are applied to a double pane bronze glass window the total PPD is increased compared to the total PPD of the plain bronze glass window. The reason is that applying film to the double pane bronze glass window, which already has rather high value of absorptance, causes the total value of absorptance of the glass window with film getting higher. Though, applying the film to the glass will cause the discomfort from the solar radiation effect reduced but it also causes the discomfort from the surface temperature increased due to high value of absorptance. The significant increase in the discomfort from the surface temperature effect for the double pane bronze glass windows with film makes the total discomfort getting higher than the plain double bronze glass window. And from figure 5, it is also interesting to see that though the value of the total PPD (discomfort condition) of the single pane clear glass is greater than the value of the total PPD of the double pane clear glass, but when film is applied to the glass windows the effect of the discomfort is reversed; the total discomfort from the double pane clear glass windows with film is higher than the total discomfort from the single pane clear glass window with film of the same type. Therefore, it can be said that applying film to glass windows usually causes the total discomfort to be reduced (increase discomfort due to surface temperature and reduce discomfort due to solar radiation) but one has to be very careful when applying film to double pane glass windows, especially the double pane tinted glass windows, to reduce the discomfort effect.

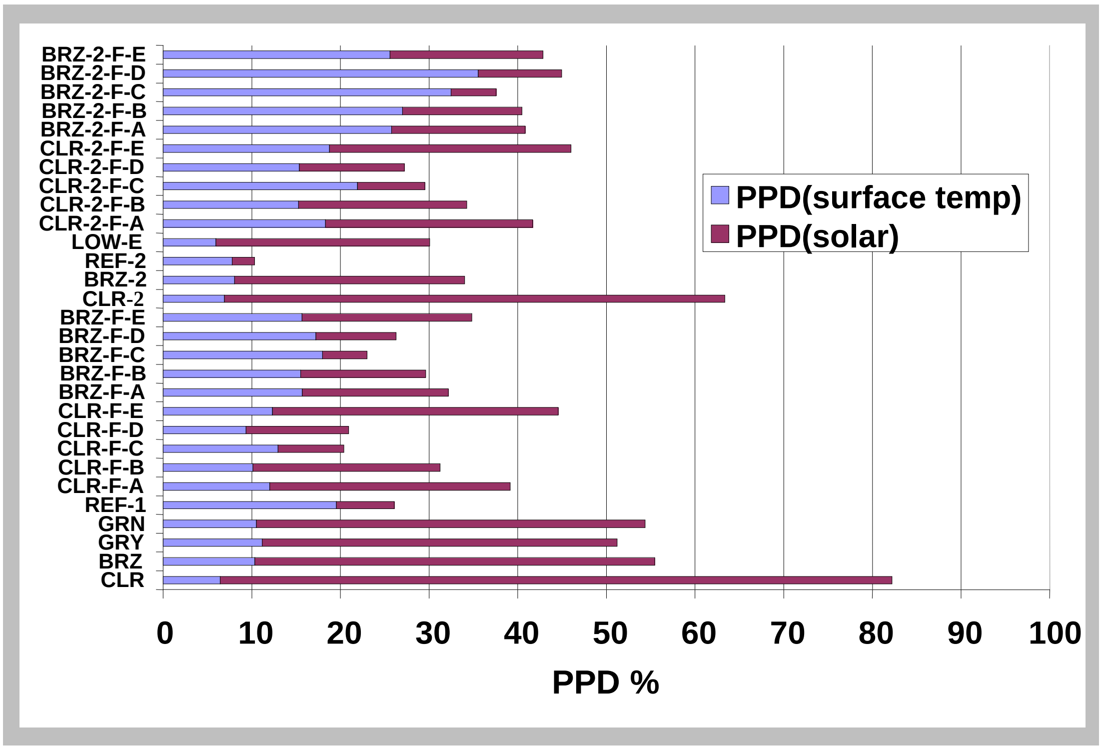


Figure 5
Values of the thermal comfort index (PPD) for different glass and glass with film (group A to E). CLR = single pane clear glass, BRZ = single pane bronze glass, GRY = single pane grey glass, GRN = single pane green glass, REF-1 = single pane reflective glass, REF-2 = double pane reflective glass, CLR-2 = double pane clear glass, BRZ-2 = double pane bronze glass, LOW-E = low-e glass, F-A to F-E refer to film group A to E adhered to clear and bronze glass.

V. Expressions for predicting thermal comfort conditions

Finally all the results of glass windows with film obtained (1280 glass windows with film) are grouped together and analyzed to find some relationship between the thermal comfort index and the optical properties of glass window with film. The total optical properties of glass indow with film, transmittance and absorptance, are chosen as the representing parametersinstead of the spectral optical properties. The analysis is done by separating glass window with films into 2 groups. They are single pane clear and tinted glass with film and double pane clear and tinted glass with film.

5.1 Single pane clear and tinted glass with film

As for single pane glass window with films (640 glass window with films), the relationship between the PPD_{solar} and total transmittance and the relationship between the $PPD_{\text{surface temp}}$

and total absorptance are shown in figures 6 and 7. From figure 6 it is found that the PPD_{solar} is varied linearly with the total transmittance of the glass window with film. From figure 7, the relationship between the $PPD_{surface\ temp}$ and total absorptance falls into 3 separate curves characterized as groups 1, 2 and 3. It can be said that the discomfort from the solar radiation effect is increased with the transmittance value of the glass window with film. The discomfort from the surface temperature effect is also increased with the value of absorptance of the glass window with film. Since the summation of the three properties (transmittance, absorptance and reflectance) is equal to one. One property of glass window with film will affect the other two (i.e. glass window with film having high transmittance will have low absorptance and reflectance). Therefore, in order to choose a proper glass window with film, a balance choice between discomfort from the solar radiation effect and discomfort from the surface temperature effect has to be carefully considered. From the analysis, in the 40 types of film, there are 18 types of film that characterized as film group 1. Films in this group when applied to the glass window, the glass window with films have overall heat transfer coefficient values larger than the overall heat transfer coefficient of the glasses without film. There are 18 types of film that characterized as film group 2. Films in this group when applied to the glass window, the glass window with films have overall heat transfer coefficient values slightly less than the overall heat transfer coefficient of the glasses without film (0.1 to 8 percent). There are 4 types of film that characterized as film group 3. Films in this group when applied to the glass window, the glass window with films have overall heat transfer coefficient values less than the overall heat transfer coefficient of the glass without film about 20 percent. Table 2 shows a list of the film types in the 3 groups according to the name given in the library of OPTIC5. The relationships shown in figures 6 and 7 can be written as the following:

$$PPD_{solar} = 98.853\tau_T - 1.0723 \quad (9)$$

Film group 1 $$PPD_{surface\ temp} = 5.40401e^{1.5239A_T} \quad (10)$$

Film group 2 $$PPD_{surface\ temp} = 5.11011e^{1.5598A_T} \quad (11)$$

Film group 3 $$PPD_{surface\ temp} = 5.3676e^{1.7082A_T} \quad (12)$$

where τ_T = total transmittance
A_T = total absorptance

5.2 Double pane clear and tinted glass with film

As for double pane glass window with films (640 glass window with films) the relationship between the PPD_{solar} and total transmittance and the relationship between the $PPD_{surface\ temp}$ and total absorptance are shown in figures 8 and 9. From figure 8, it is found that the PPD_{solar} is varied linearly with the total transmittance of the glass window with film. From figure 9, the relationship between the $PPD_{surface\ temp}$ and total absorptance is quite spread out so that one cannot get an accurate expression. But on further separating double pane glass with film according to its thicknesses (3, 6, 8 and 12 mm with 6 mm air gap), the relationship between the $PPD_{surface\ temp}$ and total absorptance falls into 3 separate curves characterized as groups 1, 2 and 3 (as shown in table 2) similar to the case of single pane glass with film. It can be seen that glass window with films in group 3 have the most discomfort due to surface temperature effect among the 3 groups of glass window with films for the same absorptance. These relationships are shown in figures 8, 10, 11, 12 and 13. For the double pane glass window with film, the discomfort from the solar radiation effect is increased with the transmittance value of the glass window with film and the discomfort from the surface temperature effect is also increased with the value of absorptance of the glass window with film. The relationships are written as follows:

$$PPD_{solar} = 99.083\tau_T + 0.59 \quad (13)$$

Film group 1 on 3 mm glass $$PPD_{surface\ temp} = 3.9971e^{2.721A_T} \quad (14)$$

Film group 2 on 3 mm glass $$PPD_{surface\ temp} = 3.8922e^{2.875A_T} \quad (15)$$

Film group 3 on 3 mm glass $$PPD_{surface\ temp} = 3.9545e^{3.3891A_T} \quad (16)$$

Film group 1 on 6 mm glass $$PPD_{surface\ temp} = 3.4722e^{2.6903A_T} \quad (17)$$

Film group 2 on 6 mm glass $$PPD_{surface\ temp} = 3.2477e^{2.8652A_T} \quad (18)$$

Film group 3 on 6 mm glass	$PPD_{surface\ temp} = 3.3607e^{3.2738A_T}$	(19)
Film group 1 on 8 mm glass	$PPD_{surface\ temp} = 3.2302e^{2.6867A_T}$	(20)
Film group 2 on 8 mm glass	$PPD_{surface\ temp} = 2.9739e^{2.8738A_T}$	(21)
Film group 3 on 8 mm glass	$PPD_{surface\ temp} = 3.1706e^{3.2223A_T}$	(22)
Film group 1 on 12 mm glass	$PPD_{surface\ temp} = 2.8161e^{2.6969A_T}$	(23)
Film group 2 on 12 mm glass	$PPD_{surface\ temp} = 2.5116e^{2.917A_T}$	(24)
Film group 3 on 12 mm glass	$PPD_{surface\ temp} = 2.7255e^{3.2267A_T}$	(25)

With the information about the total optical properties (transmittance and absorptance), the change in overall heat transfer coefficient and the thickness (in case of double pane glass) of the glass window with film, the thermal comfort index of the glass window with film can be obtained from the expressions in equations 9 to 25. The discomfort condition obtained can be another important parameter to be considered in choosing a proper glass window with film for building envelope besides the reduction in heat transmission through the glass window with film.

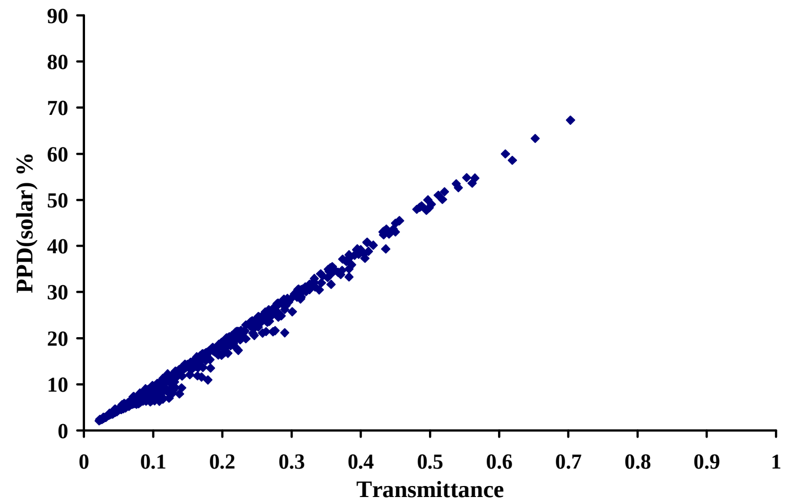


Figure 6
Relationship between the PPD due to solar radiation and the total transmittance of the single pane glass windows with film.

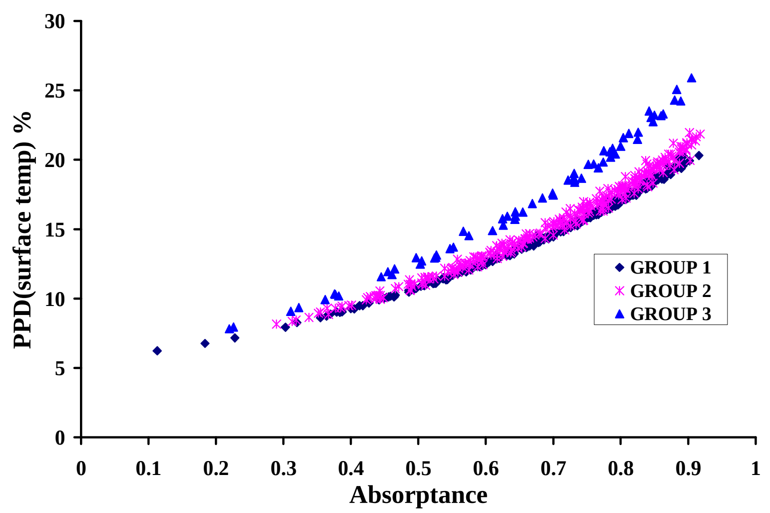


Figure 7
Relationship between the PPD due to surface temperature and the total absorptance of the single pane glass windows with film.

doi:10.4186/ej.2009.13.1.29

Figure 8
Relationship between the PPD due to solar radiation and the total transmittance of the double pane glass windows with film.

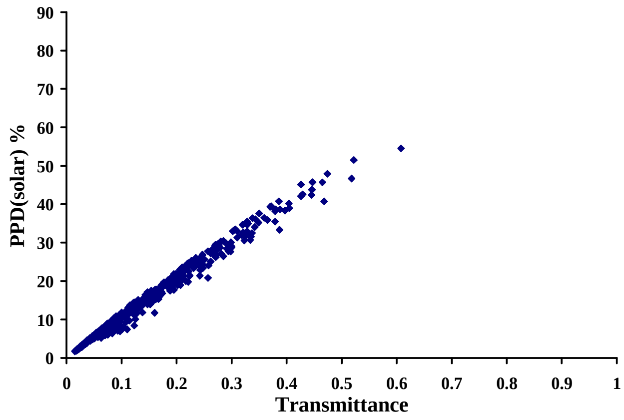


Figure 9
Relationship between the PPD due to surface temperature and the total absorptance of the double pane glass windows with film.

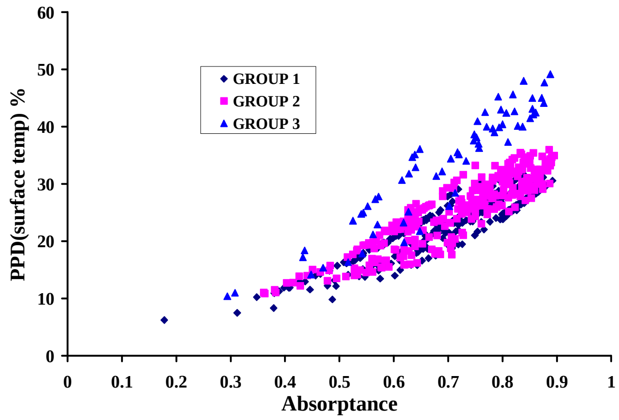


Figure 10
Relationship between the PPD due to surface temperature and the total absorptance of the double pane glass windows of 3 mm thickness with film.

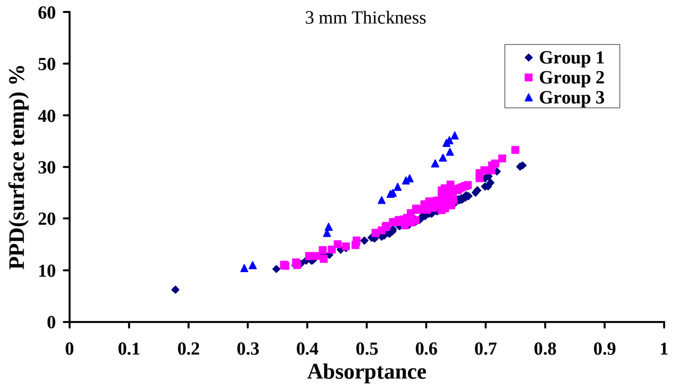
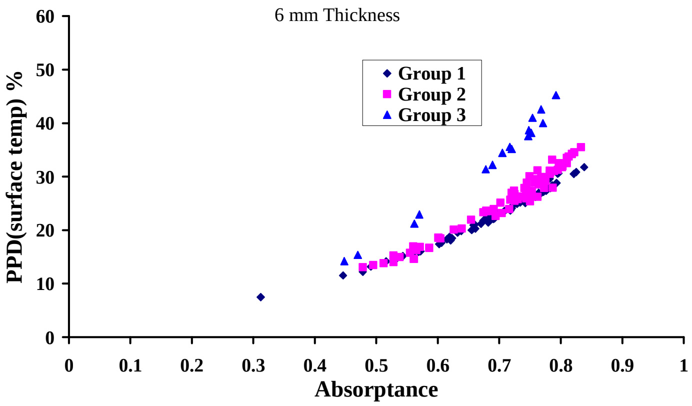


Figure 11
Relationship between the PPD due to surface temperature and the total



doi:10.4186/ej.2009.13.1.29

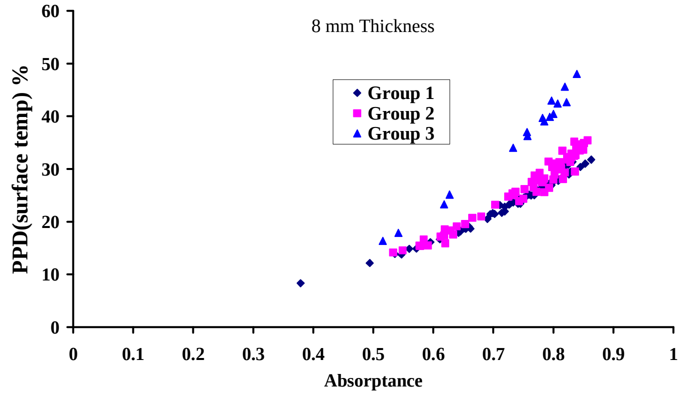


Figure 12 Relationship between the PPD due to surface temperature and the total absorptance of the double pane glass windows of 8 mm thickness with film.

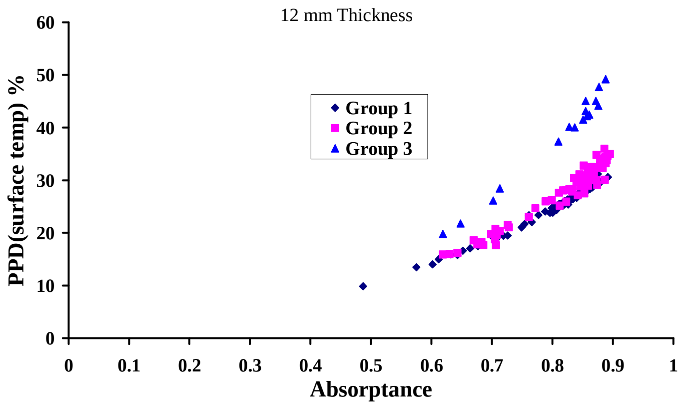


Figure 13 Relationship between the PPD due to surface temperature and the total absorptance of the double pane glass windows of 12 mm thickness with film.

VI. Conclusion

The study indicates that the total optical properties of the glass window with film; transmittance and absorptance, are the important parameters among the other parameters (change in the overall heat transfer coefficient and glass thickness, etc.) in determining the thermal performance of glass windows with film in terms of thermal comfort index (PPD). In a country located in a hot climate, most of the glass window without film (clear and tinted glass) has values of PPD due to solar radiation effect larger than the values of PPD due to surface temperature effect. Only reflective glasses, which have values of reflectance and absorptance greater than the values of transmittance, have values of PPD due to surface temperature effect higher than the values of PPD due to solar radiation effect. Film when applied to the glass windows will cause the transmittance of the glass window with film to decrease and cause the absorptance of the glass window with film to increase. Therefore glass windows with film have values of PPD due to the solar radiation effect decreased and values of PPD due to the surface temperature effect increased when compared to the plain glass windows. It is also found that the discomfort due to the surface temperature effect is increased significantly when film is applied to double pane glass windows. Care has to be taken when one wants to apply film to glass windows to reduce the heat gain because it always raises discomfort due to the surface temperature effect.

Though films in this study can be classified according to the pattern of their spectral optical properties (which have a direct effect on the performance of the glass windows with film) into 6 groups, it is interesting to find from this study that the PPD due to the solar radiation effect of all the single pane and double pane glass windows applied with 5 groups of film considered is varied linearly with the total transmittance and is not dependent on the type of film. The relationships between the PPD due to the surface temperature effect and the total absorptance of the glass windows with film can be written as three separate groups. These groups are classified according to the variation of the overall heat transfer coefficient of glass windows applied with film compared to the overall heat transfer coefficient of the plain glass windows. For double pane glass windows with film, the glass thickness becomes another important parameter in defining the relationships between the PPD due to the surface temperature effect and the total absorptance.

With the values of the change in overall heat transfer coefficient compared to the plain glass and the expressions for the relationship between the PPD and the total optical properties, transmittance and absorptance, of glass windows with film developed in this study, the thermal performance of glass windows with film on human thermal comfort can be accurately predicted.

Table 1
Film characterized according to the pattern of its spectral optical properties into 6 groups.

Film group A	Film group B	Film group C	Film group D	Film group E	Film group F
RE20NEAR_MMM RE35NEAR_MMM RE50NEAR_MMM RE70NEAR_MMM S35NEAR_MMM N1020G_CPF N1035G_CPF N1050G_CPF NRM_CPF V58_CPF V33_CPF V45_CPF	P18AR_MMM P19AR_MMM RE15SIX_MMM NRMS_CPF R20-CPF R50-CPF V28_CPF V38_CPF N1020B_CPF N1035B_CPF N1050B_CPF R15GO_CPF NV_15_MMM NV_25_MMM NV_35_MMM NV_45_MMM	R15B_CPF R15BL_CPF R15G_CPF	LE30CUAR_MMM LE35AMAR_MMM LE50AMAR_MMM	RE20BRAR_MMM RE35BRAR_MMM RE50BRAR_MMM RE25SLAR_MMM RE35SLAR_MMM RE50SLAR_MMM	PNTHR5_MMM PNTHR20_MMM PNTHR35_MMM PNTHR50_MMM NRMB_CPF

Table 2
Film characterized according to the variation of the overall heat transfer coefficient into 3 groups.

Film group 1	Film group 2	Film group 3
RE20NEAR_MMM RE35NEAR_MMM RE50NEAR_MMM RE70NEAR_MMM S35NEAR_MMM N1020G_CPF N1035G_CPF N1050G_CPF NRM_CPF V58_CPF V33_CPF V45_CPF RE20BRAR_MMM RE35BRAR_MMM RE50BRAR_MMM RE25SLAR_MMM RE35SLAR_MMM RE50SLAR_MMM	P18AR_MMM RE15SIX_MMM NRMS_CPF R20-CPF R50-CPF V28_CPF V38_CPF N1020B_CPF N1035B_CPF N1050B_CPF R15GO_CPF R15B_CPF R15BL_CPF R15G_CPF NV_15_MMM NV_25_MMM NV_35_MMM NV_45_MMM	P19AR_MMM LE30CUAR_MMM LE35AMAR_MMM LE50AMAR_MMM

ACKNOWLEDGEMENT

This research was financially supported by the National Metal and Materials Technology Center, National Science and Technology Development Agency. The authors are grateful for this support. The authors are also grateful for data support from PMK-Central Glass Co. Ltd., Thai Asahi Glass Public Co. Ltd. (Thailand), Techno-Sell (Frey) Co. Ltd. and Consulting & Management 49 Ltd.

REFERENCES

[1] "Energy Conservation Promotion Act B.E. 2535," *Department of Energy Development and Promotion (DEDP), Ministry of Science, Technology and Environment (MOSTE)*, Bangkok, 10400, 1992. [Online]. Available: http://www.unescap.org/esd/energy/publications/compend/ceccpart4chapter10.htm.

[2] "Building Control Regulation" , Building & Construction Authority (BCA) Home Page, 2003. [Online]. Available: http://www.bca.gov.sg/Publications/BuildingControlAct/building_control_act.html. [Accessed: June 12, 2007].

[3] "Energy Efficiency of Buildings - Building (Energy Efficiency) Regulation," 2000. [Online]. Available: http://www.arch.hku.hk/research/BEER/Pnap172.pdf. [Accessed: June 12, 2007].

[4] S. Chaiyapinunt, B. Phueakphongsuriya, K. Mongkornsaksit, and N. Khomporn, "Performance rating of glass windows and glass windows with films in aspect of thermal comfort and heat transmission," *Energy and Buildings*, vol. 37, pp. 725-738, 2005.

[5] M. C. Singh, S. N. Garg, and R. Jha, "Different glazing systems and their impact on human thermal comfort--Indian scenario," *Building and Environment*, vol. 43, pp. 1596-1602, 2008.

[6] ISO Standard 7730:1995, *Moderate thermal environments. Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*. Geneva, Switzerland: International Organization for standardization.

[7] ASHRAE, *Thermal Environmental Conditions for Human Occupancy*: ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers), 1992.

[8] P. O. Fanger, *Thermal comfort: analysis and applications in environmental engineering*: McGraw-Hill Inc.,US, 1973.

[9] P. R. A. Lyons, D. Arasteh , and C. Huizenga, "Window Performance for Human Thermal Comfort," *ASHRAE Transactions*, vol. 73, pp. 594-602, 1999.

[10] R. Sullivan, "Thermal comfort issues in the LRI study," Windows and Daylighting Group, Lawrence Berkeley National Laboratory, Berkeley, California , USA 1986.

[11] E. Finlayson , D. K. Arasteh , C. Huizenga , M. D. Rubin , and M. S. Reilly "WINDOW 4.0: Documentation of Calculation Procedures," Lawrence Berkekey Laboratory report,LBL-33943 1993.

[12] "Ventilation and Infiltration," *ASHRAE Handbook of Fundamentals*, R. Parsons, Ed.: American Society of Heating Refrigerating and (July 2001), pp. chapter 27, 27.1-27.71, 2001.

[13] M. Rubin , K. von Rottkay , and R. Powles "Window optics," *Solar Energy*, vol. 62, pp. 149-161, 1988.

[14] "OPTIC 5," [Online]. Available: http://windows.lbl.gov/materials/optic5/. [Accessed: Feb, 2005].