Chapter 72
Analyzing the Optical Performance of Intelligent Thin Films Applied to Architectural Glazing and Solar Collectors

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Abstract. Windows provide us with natural light and fine-looking connections to the outdoors. However, a huge amount of energy is lost through these building envelopes. Similarly, the glazing is used in many other systems such as solar collector covers and photovoltaic cells. This study reviews the most common and contemporary coatings of the glass surface with thin films. It is analyzed how the smart windows operate and help us in enhancing energy efficiency, getting the most out of indoor comfort and improving the performance of solar collectors and PV cells. These intelligent coatings feature different and selective optical properties in different environmental conditions. The analysis emphasizes on the radiation equations and discusses the different scenarios based on these equations.

1 Introduction

A significant amount of energy is consumed for maintaining thermal comfort in buildings. This energy is mostly burnt off to keep vapor compression cycles and AC devices running. The building energy consumption is noticeably high in hot and humid regions, contributing to one third to half of the electricity produced in some countries [1-3]. Therefore, energy saving measures should be implemented in order to decrease energy losses [4]. It is highlighted as a major responsibility of designers of new buildings not only to cut down on electricity consumption in lighting and HVAC systems but also to choose building materials wisely [5]. There are two approaches in energy saving strategies, the active strategies and the passive ones. Improving HVAC systems and building lighting can actively increase the building's energy efficiency, whereas measures amending building envelopes are the passive methods for the above mentioned purpose. Any building element, such as wall, roof and fenestration which separates the indoor from outdoor is called building envelope [4]. Using cool coatings on roofs, adding thermal insulation to walls and coated window glazing are among the effective envelope-based passive techniques that ameliorate energy efficiency [6-8].

Windows are known as one of the most energy inefficient components of buildings [9]. Cooling and heating energy is noticeably wasted via windows. Particularly in commercial buildings, they are excessively exposed to solar radiation due to large area fenestration leading to thermal discomfort [10, 11]. According to the National

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Renewable Energy Laboratory report 2009, windows are culpable of about 30 percent of building heating and cooling electrical loads and applying high-tech fenestration techniques can potentially save approximately 6 percent of the energy consumption nationwide [12].

Consequently, if we curtail these losses by improving the windows thermal performance less electricity costs and greenhouse gas emissions will be resulted. Therefore, controlling solar gain and loss by means of fenestration should be emphasized in building design. While reducing radiation transmitted, the window materials should be capable of sufficient transmission of visible light through windows [13]. Modern architecture lends a lot to the concept of residents' comfort [14]. From the aesthetic standpoint, these transparent facades are essential building elements that provide a comfortable indoor environment by creating eye-catching views as well as illuminating the interior space by inviting light inside [15]. Moreover, there are some goals, which cannot be achieved by conventional materials such as metals and plastics whereas glass will be suitable [16]. There is quite a vast number of parameters influencing the heat transfer through windows such as outdoor conditions, shading, building orientation, type and area of window, glass properties and glazing characteristics [15]. Improving glazing characteristics of windows such as thermal transmittance and solar parameters is the most important criterion to be considered in building windows standards [17].

In recent years, glazing technologies and materials have been the major focus of many studies. Aerogel glazing, vacuum glazing, switchable reflective glazing, suspended particle devices film, holographic optical elements [18, 19], low-e coatings, all-solid- state switchable mirror glass [20, 21], gas cavity fills and improvements in frame and spacer designs [22] are among the most common glazing technologies in terms of controlling solar heat gain, insulation and lighting. Electrochromic (EC), thermochromic (TC) and photochromic materials are employed in glass industry for different, sometimes odd, applications. The two most recent developments in the industry, "self-cleaning glass" and "smart glass", offer excellent energy efficient and environmentally friendly features in various applications [16].

1.1 Switchable Reflective Glazing (Intelligent Glazing)

This type of glass -also named "smart window"-is generally based on optical switching along with modulation in glass properties. These dynamic tintable windows are categorized in to passive and active systems.

In passive devices, the switching process is activated automatically in accordance with the environmental conditions. This environmental factor can be light in case of photochromic windows; or temperature and heat in thermochromic windows (TCW). Alternatively, the active systems require an external triggering mechanism to perform the modulation. For instance, electricity is the actuating signal in electrochromic windows (ECW). The active switchable glazing systems offer supplementary options compared to the passive systems whereas their dependency on power supply and wiring should be reckoned with as a drawback. Chromic materials, liquid crystals, and suspended particle windows are the three most common active-controlled intelligent windows [9]. The latter two share the disadvantage of their dependency on an electric field to be maintained when a transparent mode is desired; resulting in excessive electricity consumption. This is not the case in EC glazing that wants electricity only for transition [23]. However, chromic materials are classified into four types: electrochromic (EC), gasochromic, photochromic and thermochromic (TC). The first two belong to active glazing, responding to electricity and hydrogen gas respectively as a function of solar irradiation [9, 19].Smart windows are apt to glazing the cooling load demanding buildings with large solar gain [18], though providing a see-through mode is a must in any application.

The decisive factors, based on which the performance of intelligent windows can be evaluated, are ordered below with respect to their importance [9]:

1. Transmission modulation in the visible and outer visible spectrum
2. Anticipated life time and the number of cycles without degradation
3. Response time; the time required to switch between colored and bleached states, which depends on the size of the window
4. The resulted window size
5. Overall energy consumption
6. Operating voltage and temperature

We have brought different classes of switchable glazing in the following:

1.1.1 Electrochromic Windows (ECW)

The EC effect which was first explained in 1969 is a characteristic of a device which varies its optical properties when an external voltage triggers the EC material. The EC device modulates its transmittance in visible and near IR when a low DC potential is applied [24, 25].

It is usually consisted of several layers deposited on glass. The glass substrates are usually coated with transparent conducting films with natural colors-mostly tin oxide doped with either indium (ITO) or fluorine (FTO). The three major deposited layers cover the coated glass substrate as follows:

1-The Electrochromic film (cathodic electro-active layer with reversible transmittance modulation characteristic) which gets a darker color when the external circuit transfers electrons into the EC lattice to compensate for the positive ions injected from the adjacent ion storage layer, 2-Ion conductor (ion conducting electrolyte), and 3-Ion storage layer (anodic electro-active layer) that becomes darker while releasing positive ions [10, 25-28].

The electro-active layers (also named electrochromics) switch between their oxidized and reduced forms causing variations in their optical properties and colors as well. Ideally, it is desired that electrochromics act more reflective rather than absorptive in their colored state compared with their bleached mode [24].

EC windows should provide daylight while acting as a barrier to heat. Obviously, this type of window is not capable of providing both effects simultaneously [29]. The EC function can be controlled by thermal load, temperature and sunlight. The latter is stated to be the best governing parameter, especially from the comfort point of view [30-33]. All the more, self-powered EC windows are also developed using semitransparent PV cells, which provide the required activating electricity [34-42].

Figure.1a and 1b demonstrate the structure and function of EC windows.

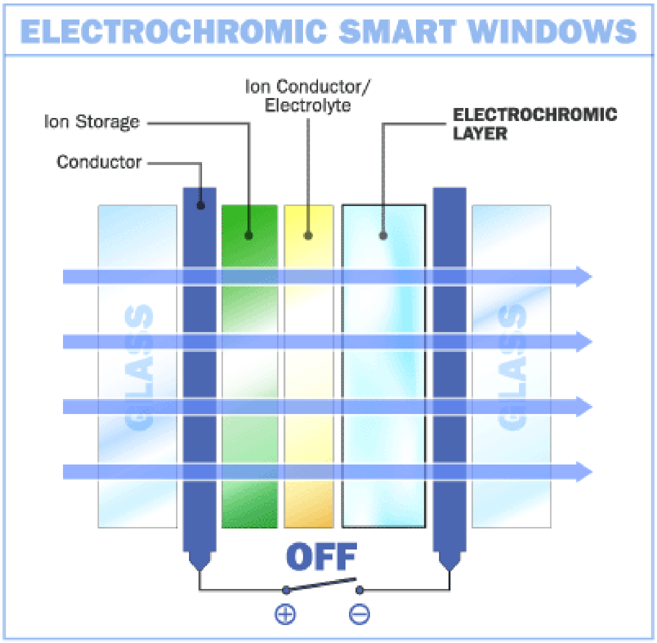

Fig. 1a. Electrochromic windows in bleached (transparent) mode [43]

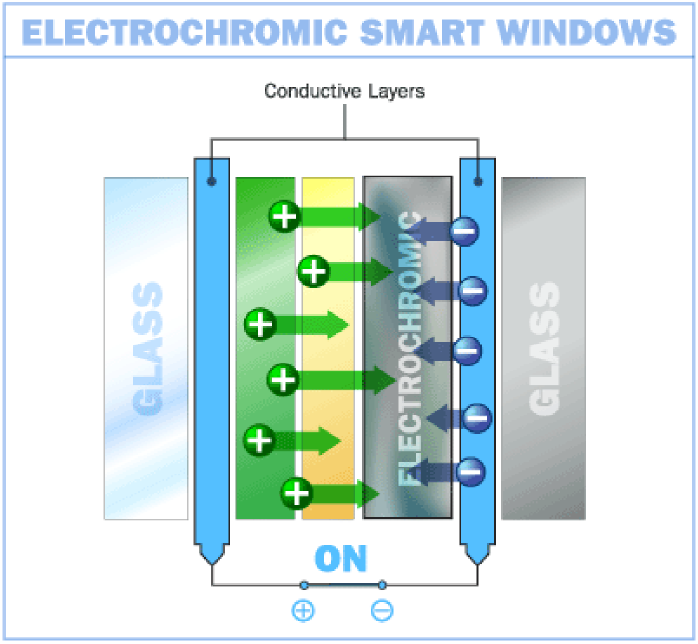

Fig. 1b. Electrochromic windows in colored (dark) mode [43]

1.1.2 Gasochromic Windows

The function of gasochromic devices is also based on electrochromism in EC windows. The main difference is that instead of DC voltage, a hydrogen gas (H2) is applied to switch between colored and bleached states. Compared to their counterpart, gasochromic devices are cheaper and simpler because only one EC layer is enough and the ion conductor and storage layers are not needed anymore. Although, gasochromic devices exhibit some merits such as better transmittance modulation, lower required voltage, staying lucid in the swap period, and adjustability of any middle state between transparent and entirely opaque; only a few numbers of EC materials can be darkened by hydrogen. Furthermore, strict control of the gas exchange process is another issue [44].

1.1.3 Liquid Crystals (LC)

Commonly used in wrist watches, LC technology is getting more popular as a means of protecting privacy in some interior applications such as bathrooms, conference halls and fitting rooms in stores. As it can be seen in Figure 2, two transparent conductor layers, on plastic films squeeze a thin liquid crystal layer, and the whole set is pressed between two layers of glass. Normally, the liquid crystal molecules are situated in random and unaligned orientations scattering light and cloaking the view to provide the interior space with privacy. When the power is switched on the two conductive layers provide an electric field via their electrodes. The field causes the

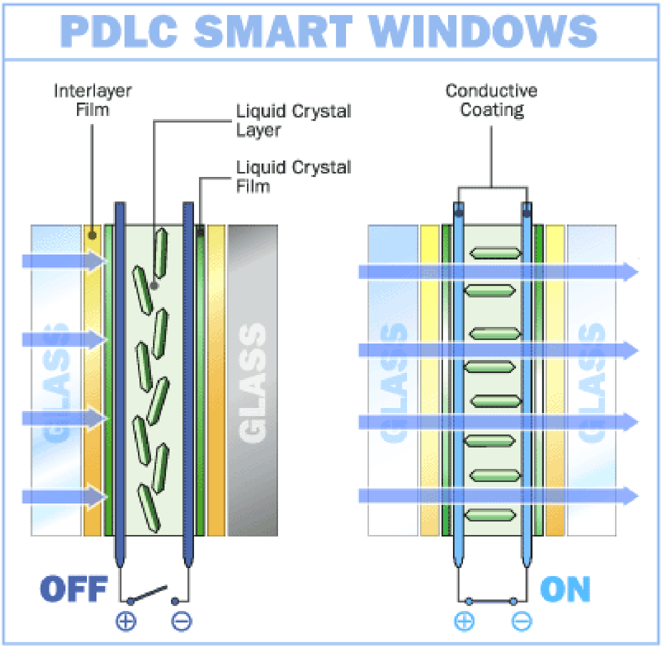

Fig. 2. PDLC technology used in smart windows [43]

crystal molecules to be positioned in an aligned direction causing a change in transmittance [45, 46]. The LC technology suffers from the disadvantage of high power demand in transparent mode, resulting in an electricity usage of 5-20 W/m2. These devices have problems, in long term UV stability and high cost disadvantages as well [9]. The technology using liquid crystals in intelligent windows is called Polymer dispersed liquid crystals (PDLC) which is illustrated in figure 2.

1.1.4 Electrophoretic or Suspended-Particle Devices (SPD)

SPDs have many things in common with LC devices: they are both fast in switching between phases, high electricity consumptive and dependent on an electric field. Figure 3 shows the construction and operation of SP windows. According to the figure, they consist of the liquid like active layer formed by adsorbing dipole needle-shaped or spherical particles (molecular particles), i.e. mostly polyhalide, suspended in an organic fluid or gel sandwiched between two sheets of glass coated with transparent conductive films. Normally, the device is in the dark reflective state because of the random pattern of the active layer's light absorbing particles. When the electric field is applied, the particles will align resulting in the clear transmissive state. As soon as the power turns off the device switches to its dark state. Typically, the transmission of SPDs varies between 0.79-0.49 and 0.50-0.04, with 100 to 200 ms switching time and 65 to 220 V AC requirements [9].

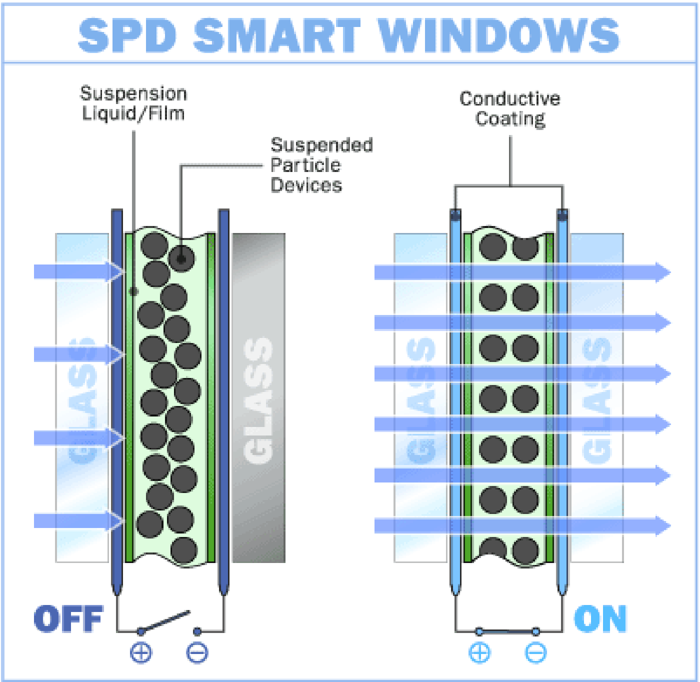

Fig. 3. Suspended particle device in smart windows [43]

1.1.5 Thermochromic windows (TCW)

A thermochromic material changes color as the temperature changes [47]. TCW is a device on which a thin film of TC materials is deposited. This can reduce the energy demand of buildings by changing the device's reflectance and transmission properties, reducing the solar energy gain [48, 49]. The TC thin film is initially in its monoclinic state at lower temperatures (usually room temperature). Monoclinic materials behave as semiconductors, less reflective, especially in near IR radiation. As the temperature rises, the TC material changes its nature from monoclinic to the rutile state. This effect is called metal to semiconductor transition (MST). In the rutile state, the material acts like a semi-metal, reflecting a wide range of the solar spectrum [50]. In high temperatures, it blocks near-IR (800-1200 nm) the wavelengths from which most of the heat is originated and far-IR (1200-2500 nm) while in low temperatures it allows those parts of the spectrum to pass [51].

2 Optical Analysis

In the previous sections, we reviewed the common intelligent glazing. The smart coatings are deposited on the glass surface and they amend the optical properties of the surface regarding wavelength and environmental conditions.

A typical sketch of the coating on a glass surface is demonstrated in figure 4. As it can be observed, the radiation will be reflected on two surfaces, first on the coating and second the coating-glass interface.

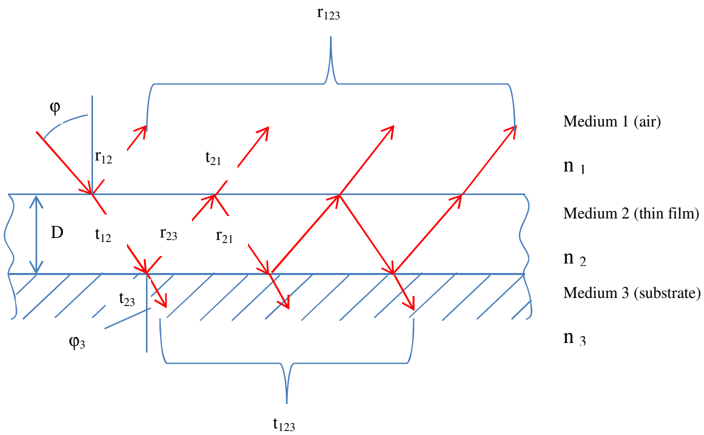

Fig. 4. The continuous reflections and transmissions through a thin film coated on the surface of substrate

As it is observed in the figure, the incident radiation first hits the coating surface (first surface). A fraction of the radiation gets reflected (r12) and the rest pass through the coating (t12) until it reaches the thin film- substrate interface (second surface). The second surface also reflects a portion of radiation (r23) and lets the remaining pass through (t23). The reflected part again reaches the first surface on which it can whether be reflected (r21) again or transmitted (t21).

Considering the phase difference (2δ) between r12 and t21 the following equations are obtained for the overall transmission and reflection [52, 53].

$$r_{123} = \frac{r_{12} + r_{23}e^{2i\delta}}{1 - r_{21}r_{23}e^{2i\delta}} \tag{1}$$

$$t_{123} = \frac{t_{12}t_{23}e^{i\delta}}{1 - r_{21}r_{23}e^{2i\delta}} \tag{2}$$

Where, for φ as incident angle, the phase gain can be calculated by equation (3).

$$\delta = 2\pi v D\sqrt{n_2^{\ 2} - \sin^2\varphi} \tag{3}$$

Therefore, the reflected and transmitted energy of the film-substrate shown in figure 4 can be estimated using equations (4) and (5).

$$R = | r_{123} |^2 \tag{4}$$

$$T = \frac{\mathrm{Re}(n_3 \cos\varphi_3)}{\mathrm{Re}(n_1 \cos\varphi)} | t_{123} |^2 \tag{5}$$

Finally, the absorptance of the whole system will be

$$A = 1 - T - R \tag{6}$$

The absorbed incident energy of a solar collector plate with αc absorptivity can be computed by equation (7) [54].

$$A_c = \frac{\alpha_c T}{1 - (1 - \alpha_c)R} \tag{7}$$

If normal incidence is the going to be analyzed equation (8) can be introduced in which the Fresnel's formulae have been employed to simplify the equations using only refractive indices of the layers.

$$R = \frac{n_2^{\ 2}(n_1 - n_3)^2 - (n_1^{\ 2} - n_2^{\ 2})(n_2^{\ 2} - n_3^{\ 2})\sin^2(2\pi n_2 D/\lambda_0)}{n_2^{\ 2}(n_1 + n_3)^2 - (n_1^{\ 2} - n_2^{\ 2})(n_2^{\ 2} - n_3^{\ 2})\sin^2(2\pi n_2 D/\lambda_0)} \tag{8}$$

Where, λo is the wavelength in vacuum.

3 Discussion and Conclusions

The ideal windows are those, which let the light pass through in the visible range and block the unwanted radiation which cause heat loss or heat gain regarding the climate. The smart coatings such as electrochromic and thermochromic thin films feature spectrally selective behavior in the different wavelengths. Accordingly, in the visible range (400 nm – 700 nm) they are highly transmissive and in the near infrared (NIR) range (700 nm- 2500 nm) the reflectivity and transmissivity change in response to external triggers such as electricity, light and temperature. The infrared radiation is the greatest contributor to heat among the different sections of spectrum [55].

In order to compare different glazing technologies we should first define which goals take priority over the others. Do we want to block the IR radiation in the price of losing view or the view is more important? Is lighting energy is of more importance than cooling energy? Is the resulted color of the window important? How desirable is privacy?

Obviously, each coating has different effects on different parts of spectrum and results in diverse colors. Table 1 compares TC glazing, EC windows, LC technology and SPD in terms of their thermal effect, optical effect, visual performance, the activating factor and the challenges of these technologies. TC and EC windows show better upshot in reducing transmission and providing outside view.

Table 1. A comparison between Thermochromic, electrochromic, Liquid crystal and suspended particle devices [56]

	Thermal performance	Optical performance	View	Actuator	Challenge
TC	Reducing transmitted radiation UV transmissive in colored mode; operates best in the near IR	Low transmission in visible range	Transparent at high IR ; reduction in light intensity but still transparent	Heat (surface temperature)	Low visibility (can be solved by choosing the suitable dopant)
EC	reducing transmitted radiation	transparent in the short wavelength region coupled with opacity in the long wavelength region	Reduction in light intensity	Voltage or current	Electric field dependent; Wiring required
LC	Low reduction in transmitted radiation	Opaque in colored mode	Reduction in visibility; opaque	Voltage	High electricity consumption
SPD	Low reduction in transmitted radiation	Opaque in colored mode	Reduction in visibility; opaque	Current	High electricity consumption

As it is demonstrated in figure 5, electrochromic and thermochromic windows are the best glazing types in terms of reducing the required cooling load. As it is mentioned earlier in introduction, one of the most crucial parameters in evaluating the performance of smart windows is transmission modulation and their ability to pass through the visible light. Thermochromic and electrochromic windows fulfill this requirement. The overall energy consumption will also plunge considerably by using these two chromogenic smart windows. However, the necessity of wiring in electrochromic glazing and the better ability of thermochromic windows to maintain the visible transmission when it is properly doped [57] besides their simple structure [58] have given thermochromic windows a cutting edge compared to the other counterparts.

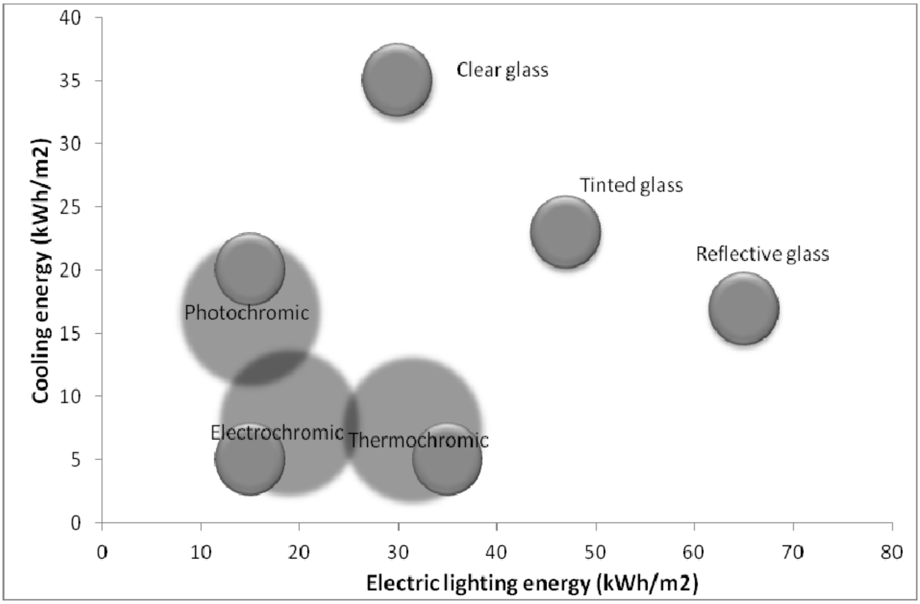

Fig. 5. Comparison of electric lighting energy and cooling energy between different glazing types adapted from Ref. [59]

Considering equation (8) it is clear that in order to acquire lower reflectivity, the refractive index of film should be lower. Hence, according to the application one should select the type of thin film and the value of refractive index. For fenestration in hot climates the desired window should be highly reflective in infrared while being transmissive enough to the visible light [60]. In this case, films should have higher refractive index in near infrared and should show lower refractive index in visible range. For instance, thermochromic thin films should have this characteristic in order to be effective in saving energy. According to experiments, at temperatures below the transition temperature, thermochromic films show higher reflectivity in visible range and lower reflectivity in NIR range. Whereas, at temperatures higher than transition point the optical properties are just reverse [50].

For the case of solar collectors, in order to absorb more energy, besides the high absorptivity of the plate itself the optical properties of the glass cover should show a desirable trend. Based on equation (7) it is concluded that the glass cover should have higher transmissivity and lower reflectance. Using smart thin films, which are more transmissive, especially in the visible range, can live up to this goal. However, it should be taken into consideration that beside the optical performance of the glass cover itself, there are some other omnipresent parameters, such as dust and humidity that can affect the level of solar absorption [61].

To recapitulate, it can be stated that until now, many experiments have been conducted on the optical performance of smart thin films but there is not enough attention to the optical equations available. Through elaborating the equations in this study, a systematic approach is constructed to evaluate performance of thin films coated on glass substrates.

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