COMMENTARY

Spectrally selective coatings on glass: solar-control and low-emissivity coatings

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Increased living standards in the developed world, as well as in developing countries, have made air conditioning very popular. It is estimated that energy consumption for air conditioning in developing countries will continuously increase from 115 TWh in 2005 to 757 TWh in 2030 [1]. In comparison, energy consumption for cooling residential spaces in the United States will level off and stay constant at around 200 TWh during the same period of time.

Glass is widely used in commercial and residential buildings, and automobiles. For these applications, there is a tendency to increase the area covered by windows aiming at increased visual comfort and aesthetics. However, glass does not allow control over infrared (IR) radiation, and thus heat control through the windows is not possible. This way, IR radiation entering buildings and automobiles results in increased temperature. In the case of cars, windows contribute up to about 70% of the total heat, and nearly half of this figure is from windshields [2]. Moreover, energy used for room heating is lost by radiation through the windows. As such, efficient use of energy in air conditioning, i.e. control of IR radiation through windows, becomes desirable since it would result in reduced energy consumption, resulting in energy savings and contributing to reduce global warming.

Highly transparent thermally reflective coatings are deposited onto glasses to be used in windows for the purpose of saving energy. These are generally termed spectrally selective coatings, and include solar-control coatings and low-emissivity coatings.

Before describing the fundamentals of spectrally selective coatings, it is necessary to keep in mind that all matter emits radiation. To describe radiation from matter the concept of blackbody is introduced. A blackbody is usually defined as a perfect radiator which absorbs all radiation incident upon it [3]. Planck's Law describes the amplitude of electromagnetic radiation emitted (spectral radiance) from a blackbody. If the wavelength, λ, is given in microns and temperature, T, in Kelvin, Planck's Law takes the form [3]

$$W_\lambda(\lambda,T)=\frac{C_1}{\lambda^5\left(e^{C_2/\lambda T}-1\right)}, \tag{1}$$

where C_1 = 37,418 and C_2 = 14,388 when the area is in square centimeters. W_λ is then given in Wcm^{-2}µm^{-1}.

Figure 1 (top) shows the blackbody spectra at four different temperatures (-50 ºC, 0 ºC, 25 ºC and 50 ºC) as predicted by Eq. (1). It is noted that a blackbody at room temperature mostly emits in the IR range. It is also observed that increased temperature results in peak-emission shift toward shorter wavelengths (Wien's displacement law), as well as increased area under the curve, i.e. increased total energy radiated (Stefan-Boltzmann law). For temperatures above

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hundreds of degrees visible wavelengths are emitted. In fact, the sun can be regarded as a blackbody with T ~ 5800 ºC.

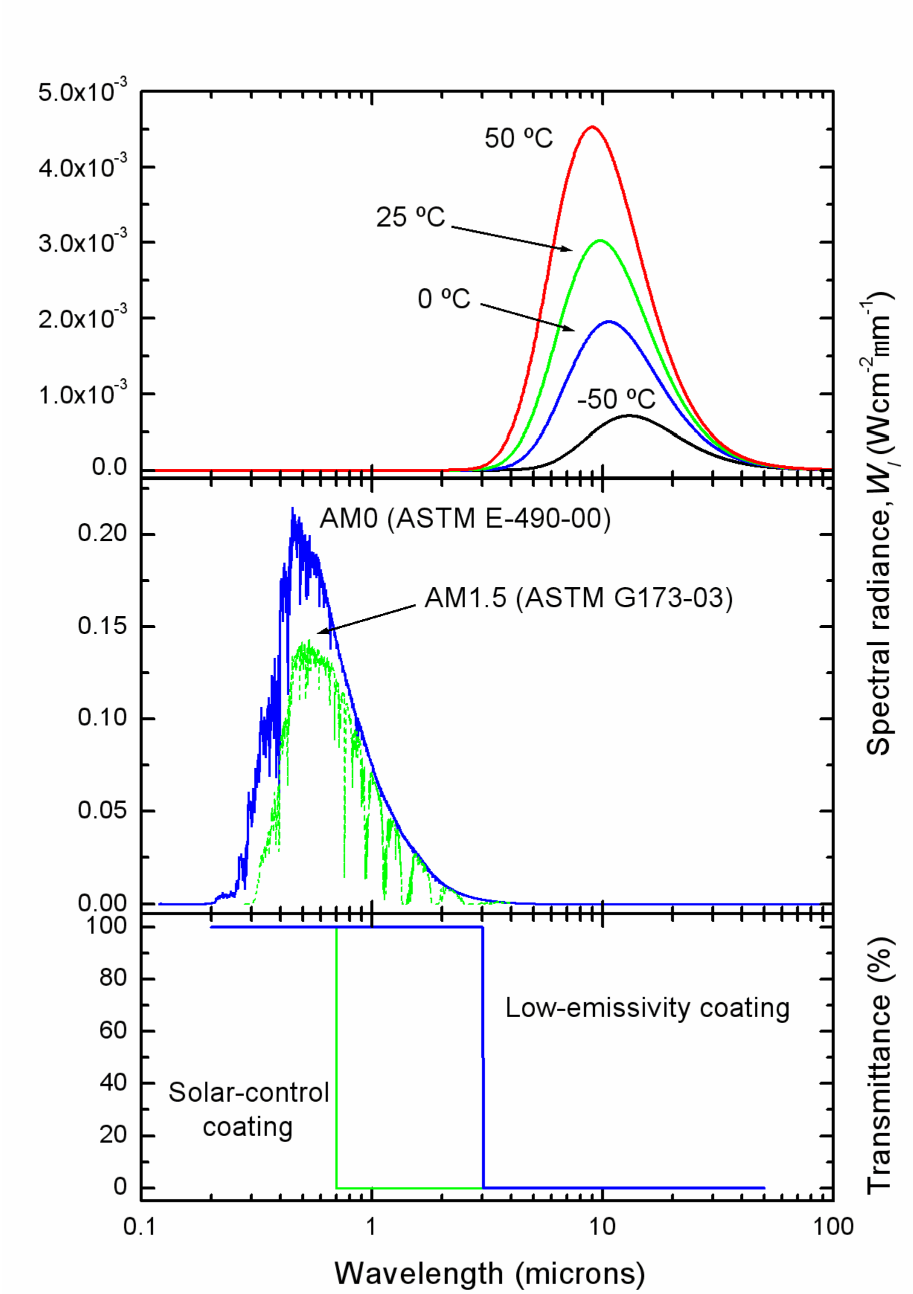

Fig. 1. (top) Blackbody spectra at four different temperatures (-50 ºC, 0 ºC, 25 ºC, and 50 ºC). (middle) Standard extraterrestrial solar spectrum (AM0, 2000 ASTM E-490-00), and terrestrial reference spectrum for photovoltaic performance evaluation (AM1.5, ASTM G173-03). The AM0 spectrum is based on data from satellites, space shuttle missions, high-altitude aircraft, rocket soundings, ground-based solar telescopes, and modeled spectral irradiance. (Data retrieved from the Renewable Resource Data Center, National Renewable Energy Laboratory). (bottom) Idealized transmittance spectra for solar-control and low-emissivity coatings.

Figure 1 (middle) shows the solar spectrum just outside the atmosphere. This spectrum is generally known as Air Mass Zero (AM0). Fig. 1 (middle) also shows the AM1.5 spectrum, which is the standard solar spectrum used for photovoltaic performance calculations. This spectrum takes into account absorption by the atmosphere. The AM1.5 spectrum shows absorption bands caused mainly by water vapor, carbon dioxide, and ozone [4]. It is observed that in some ranges absorption from the atmosphere is very strong.

From a practical point of view, it is noteworthy that the AM0 and AM1.5 solar spectra are confined to the 250 nm to 3 μm wavelength range. These spectra peak at around 555 nm, coinciding with the maximum relative sensitivity of the human eye. The IR part of the solar spectrum (0.7 to 3 microns) accounts for about 50% of the total solar energy [4]. Additionally, as can be inferred from Fig. 1 (top and middle), there is practically no overlap between thermal radiation at room temperatures (Fig. 1, top) and the solar spectra (Fig. 1, middle). This is a key fact in the development of spectrally selective coatings for thermal control.

Figure 1 (bottom) shows the idealized transmittance spectra for solar-control coatings and low-emissivity coatings. First and foremost, a common requirement for coatings on glass is that, ideally, they should provide 100% transmittance over the visible wavelength range (400 nm to 700 nm). Reduction of transmittance in this range would result in lower visibility and poor use of light from the sun. Additionally, it is important that, although not providing 100% transmission of visible light, both the reflection and transmission curves be flat or at least symmetrical. Otherwise, this might result in undesired internal or external coloration, having a relevant effect both on the internal visual comfort and/or on the external appearance of a building or car.

In cold climates, it is desired that the coating would allow incoming IR radiation from the sun and, at the same time, the IR radiation from the inside must not be radiated through the windows. For this reason, a low-emissivity coating should ideally provide 100% transmission in the IR part of the solar spectrum and 100% reflectance in the 3 μm to 50 μm wavelength range.

In warm climates, however, the IR part of the solar spectrum would result in unwanted room heating. Additionally blackbody radiation needs to be blocked to prevent heating from the outside. Accordingly, a solar-control coating should ideally provide 100% reflectance in the 0.7 μm to 50 μm wavelength range.

The most widely used spectrally selective coatings in the industry are of two types: wide band gap heavily-doped semiconductors and thin films of metals.

Wide band gap heavily-doped semiconductors should have a sufficiently wide bandgap to allow high visible transmission and, at the same time, enough free carriers to show large IR reflectance. The most commonly used spectrally selective semiconductors are based on Sn, In and Zn. These materials are generally used as low-emissivity coatings. However, these are less useful for solar-control since generally the doping level cannot be made as high as to provide large reflectance in the IR part of the solar spectrum [4]. On the bright side, these coating usually provide large chemical and mechanical stability.

It is worth noting that polymer sheets and foils doped with nanoparticles are being increasingly used as solar-control coatings in windows for buildings. Nanoparticles that have been studied include indium tin oxide (ITO), antimony tin oxide (ATO) and lanthanum hexaboride [5].

Metal-based spectrally selective coatings must be thin enough to provide high visible transmittance, but thick enough to show large IR reflectance. Thin films of Ag, Cu, Au, and Al fulfill these requirements [6]. Although this is a quite straightforward approach to implement spectrally selective coatings, thin metal films are easily degraded when exposed to the atmosphere. For this reason metal-based multilayer coatings are generally preferred over single metal films. The use of dielectric interference films between the metal layers results in reduced reflectance in the visible range and increased IR reflectance. Moreover, the dielectric layers also have important functions as nucleation and protective surfaces [7]. Metal-based multilayer coatings have been developed using Cu, Au, and Ag as metal layers and ZnO, Bi_2O_3, TiO_2, In_2O_3, SnO_2, and ITO as the oxide layers. Multilayer coatings can be designed to provide solar-control or low-emissivity behavior by the proper selection of the metal/dielectric system and the thickness of the individual films.

Silver has been extensively regarded as the best choice as the metal layer because of its high infrared reflectivity and comparatively low absorption in the visible. In particular, low-emissivity multilayer coatings based on a very thin Ag (~ 90 Å) film surrounded by two SnO_2 (~ 380 Å) films have been demonstrated to provide effective heat isolation given their low emissivity values, as well as good optical properties in the visible range thus not deteriorating the optical performance of the glass substrate [8,9].

Summarizing, spectrally selective coatings can be used to provide effective control of radiation losses both in warm and cold climates. Their widespread use would result in reduced energy consumption, thus contributing to reduce global warming. However, solar-control and low-emissivity coatings provide *static* optical properties, i.e., their properties cannot be dynamically changed as a function of the particular season. In the future, it would be desirable to develop coatings which change their properties as a function of the external conditions; not only for different seasons, but for weather changes within single days. There is some current activity in the field of chromogenic materials aiming at this end.

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