

A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment



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ABSTRACT

The ever increasing demand of energy consumption, and harmful CO₂ emission, which causes global warming necessitate the urgent need of energy conservation particularly in buildings which are one of the energy consuming sectors. The most vulnerable building parts to heat gain and heat loss are windows that count for substantial cooling and heating load consequently. An enormous amount of electrical energy is being consumed to run air conditioner devices to adjust the temperature of living spaces and inside buildings, while proper glazing technologies and materials can be utilized to reduce the energy consumption. With the advancement of glazing technology, smart, passive, and active windows are developed that can considerably decrease buildings energy demands while improving indoor environment. This paper rigorously reviews various types of glass coatings and glazing systems including conventional, advanced, and smart and highlights their paramount features. The relative merits of various coatings fabrication methods are elucidated. Finally based on touchstone for different climate types, the possibility of employing different window technologies is discussed for hot, cool, and temperate climates.

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1. Introduction

Buildings consume enormous amounts of energy worldwide to maintain indoor temperature. Particularly the energy consumption of residential and commercial buildings in developed countries are continuously increasing more rapidly, witnessing the amounts ranging from 20% to 40% and the number has surpassed the energy consumption required in transportation and industrial sectors [1]. Due to the considerable difference between windows heat transfer coefficient and other building fabrics, a large amount of energy is dissipated. For instance, in a two-story house where 30% of walls are covered with windows, up to 60% of energy is lost through these windows [2]. In the United States, the Federal Office of Energy Efficiency has estimated 10–25% heat loss is due to residential building windows [3]. Heat loss through glazing in northern China is approximated to be 40–50% of the winter heating load [4]. Furthermore, artificial lighting accounts for 14% of electricity consumption in the European Union and 19% of electricity

consumption worldwide [5]. A considerable amount of these energy losses and usage may be eliminated by employing enhanced glazing technologies and windows.

Windows are directly related to thermal, light comfort, and skin health [6], in addition, they provide vision, air ventilation, acoustic comfort [7], and photo-protection [8], and they have biopsychological effects [9]. There is also an increasing trend in their usage as building facades. These vital key roles of windows necessitate their design and selection from several aspects especially energy usage and visual comfort.

Compared to insulated walls, an unshaded glass heat transfer can be hundred times higher [10], therefore various systems such as internal, and external blinds [11], single, and double curtain [12], roller shade [13], window shutter [14], angular selective shading systems [15], different coatings [16], films [17], and multiple pane windows [18] are employed to reduce the heat transfer and to control solar light.

With the development of various window technologies, investigation of their properties and characteristics in comparison to more conventional window types are essential for employing them in different climates to enhance energy saving and more comfort living environment. At first, this paper covers the basic definitions and ideal window followed by discussing more conventional glazing

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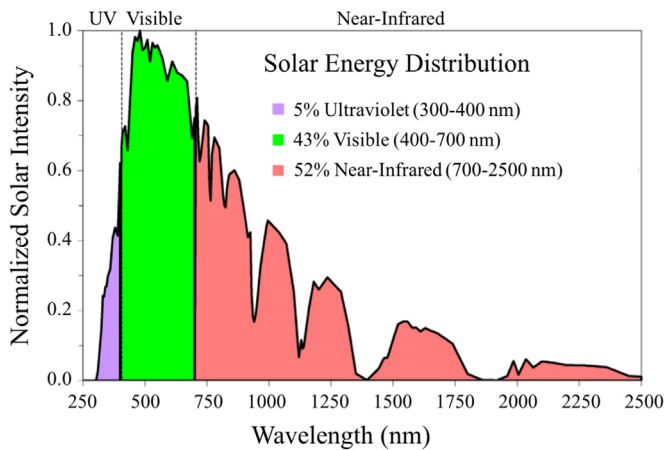


Fig. 1. Solar energy distribution. Caption in the figure has been enhanced for clarity.

Table 1

Suggested window properties for different climates. Adapted from Ref. [25] with permission from Elsevier Ltd.

Climate	T_v	SHGC	U ($\text{W m}^{-2} \text{K}^{-1}$)
Cool climate (prevailing heating loads)	> 0.70	> 0.60	< 2
Temperate climate (prevailing heating loads)	> 0.70	> 0.50	< 2.5
Hot climate (prevailing cooling loads)	> 0.60	< 0.40	< 4

glasses and coatings, including tinted glass, reflective glass, low-emissivity (low-E) coatings, multiple-pane glazing. Furthermore, low-E coating deposition techniques and processing details are investigated for different materials. Advanced technologies including aerogel, photochromic, and photovoltaic are investigated. In the next part, smart technologies including active and passive are studied extensively. Deposition techniques and materials employed in fabricating thermochromic coatings are discussed. Various functional advantages of the above-mentioned technologies are recapitulated and compared, potential usage of investigated technologies is recapitulated for cool, temperate, and hot climates. A pivotal factor that holds back new technologies from entering the market and having practical applications is the lack of industrially scalable fabrication technique. At the end of this paper, main deposition techniques suitable for commercial coatings are compared regarding their functional advantages.

2. Ideal window

When the sun ray reaches glazing material, it is either transmitted, reflected, or absorbed by the glazing depending on its

optical properties. Sun ray consists of visible, and invisible radiation and over a broad spectrum of wavelengths. Solar energy is distributed differently among these spectra. As it can be seen in Fig. 1, the solar energy distribution is different for various wavelength [19]. Solar energy from invisible solar spectrum comprises more than 50% of the solar energy [20]. Controlling the invisible solar spectrum using different glazing materials, and coatings can play a significant role in building energy savings.

Three key parameters are used to evaluate the performance and characteristics of glazing and windows. Overall heat transfer coefficient (U), visible transmittance (T_v), solar heat gain coefficient (SHGC), and emissivity. T_v is a factor for visibility of glazing material [21] and is the portion of visible light that passes through the window [22]. SHGC is the measure of solar thermal energy transmitted directly or indirectly (absorbed and then transmitted inward) and ranges from 0 to 1 for which higher value means higher solar heat transmitted [23]. Finally, U indicates heat loss of window arisen from indoor and outdoor environment temperature difference [24]. Table 1 captures the window properties suggested for three climates [25].

Windows should have different properties for various climates. The ideal window for hot climate is a window that reflects all the infrared radiation (including from sun and environment), and UV, allows all visible light to enter and is completely transparent to the infrared radiation from the inside. For cold climates, the ideal window allows all radiation wavelength from outside except UV and reflects all radiations from the inside [26]. In addition, for the ideal window, overall heat transfer coefficient should be zero for all climates. Ideal window is illustrated in Fig. 2 [26].

In practice, the ideal window with the desired properties is difficult to achieve; however, there are some specific property requirements for different climates as provided in Table 1 which are achievable.

3. Conventional glazing materials and coatings

In this part, conventional glazing related materials and coatings are investigated. Clear glass, tinted glass, low-emissivity coatings, and multiple-pane glazing are discussed in the following sections. Detailed processing schemes, materials and the state-of-the-art research regarding low-emissivity coatings are discussed as well.

3.1. Soda-lime glass

The glass is an inorganic material with an amorphous and non-crystalline structure which results from the fusion of silica with a basic oxide [27]. Soda-lime glass is produced through the floating process [28]. This glass is mainly composed of 71–75% by weight silica SiO_2 , 12–16% sodium oxide Na_2O from Na_2CO_3 known as soda, and 10–15% lime CaO , and a small amount of other materials

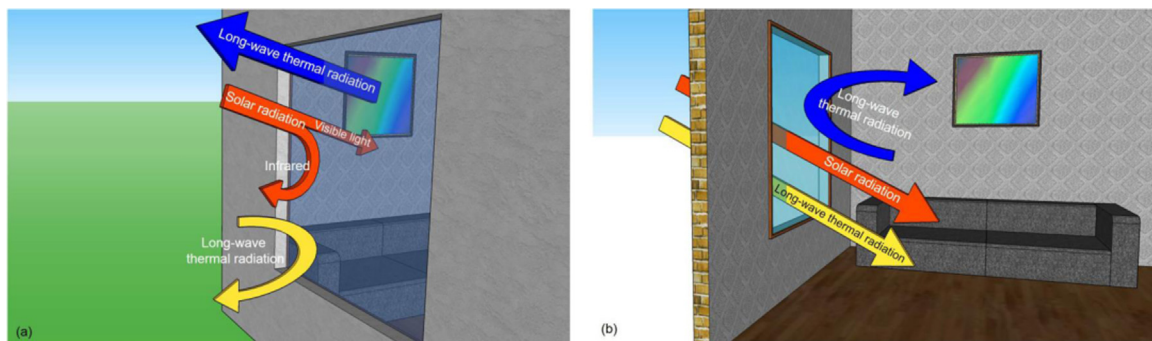


Fig. 2. ideal window optical properties for (a) Hot climate (b) cold climate. Reprinted from Ref. [26] with permission from Nature Publishing Group.

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