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Review

Solar energy materials for glazing technologies

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ABSTRACT

Although window is the main medium for the lighting of the building, it contributes significantly in the building's energy consumption, either commercial or residential. In the general frame of a growing world population and consequently of an increasing demand for reducing energy consumption for building needs, the development of appropriate glazing materials towards the maximum reduction of energy losses or gains is a major pre-requisite of modern architecture and thus of intense research in recent years. In this review, new work on insulating, reflecting, electrochromic, thermochromic, photovoltaic, water flow-based and emerging innovative materials is presented in an attempt to reveal the benefits of each glazing category but also the required research needs for future development. High energy savings can be achieved by integrating innovative transparent components in the building envelope. Insulating materials have reached a very low thermal conductivity in their sensible heating and recent complex radiative cooling multi-coatings have proved that temperatures even below the ambient can be reached indoors. Glazing integrated PVs, are among the most promising solutions due to heating and cooling savings in addition to electricity production. Finally, the combination of different panes in double glazing windows can optimize the environmental solar interaction of windows and maximize building energy savings.

Contents

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Nomenclature

IR	infrared
NIR	near infrared
UV	ultra-violet
SHGC	solar heat gain coefficient
U-value	rate heat loss, W/m^2 K
PCMs	phase change materials
PCMW	phase change material window
HW	hollow window
s–s	solid-to-solid
Tvis	visible transmittance
Tsol	solar spectrum transmittance
LE	low-emissivity
AR	anti-reflective
Δsol	energy loss

1. Introduction

If temperature increase should be kept below 2 °C by the end of the century, the majority of known hydrocarbons must remain underground. According to a recent research [1], one third of oil reserves, half of natural gas reserves, as well as 80% of coal reserves must be left in place at least until 2050. Though, the world population from seven billion (2013) is estimated to reach 10 billion or more until 2100 and this is expected to have unpleasant consequences on the availability of raw materials. Global temperature is also expected to rise and what makes the issue of temperature even more intractable are the severe effects of urban heat islands [2]. The phenomenon of city centers possessing much higher temperatures than their rural areas can lead to harmful diseases [3] and even to human conflict.

Thus, the use of conventional energy should be drastically reduced. Buildings are huge energy consumers since their functions like cooling, heating, lighting and ventilation require large amounts of energy, approximately 30–40% of consumed energy worldwide. Because of the continuing population increase, and as a consequence, of the consumed energy, mitigation measures of this phenomenon are urgently needed. In this direction, a European Directive (2010/31/EU) for nearly zero-energy buildings after 2020 has been issued [4].

Windows are a key factor in building energy, because thermal energy that is transferred through their transparent surface is decisive. During summer, windows allow heat to pass in the building and during winter, heat escapes. It is estimated that windows are responsible for 40% of the total building energy losses [5–10].

Concerning heat transfer, it would be ideal for a window to adapt its thermal properties to outdoors environmental conditions. But also, windows, like essential architectural elements, should provide the essential functionality to make the resident or the worker feel comfortable and reduce glare while permitting building's lighting. Therefore, windows functionality in the modern architecture is complex and vital.

Before reviewing recent results on the innovative solar glazing technologies, it is indicative to discuss briefly the different processes involved in the solar interaction with the glazing materials. As it can be seen for a single pane glazing in Fig. 1, a part of the incident solar radiation is reflected while another part is transmitted. The remaining is absorbed in the glass and it can be transferred inside and outside by convection, longwave radiation and conduction.

There are two main factors characterizing windows energy performance: *U*-value and *g*-value (or Solar Heat Gain Coefficient, SHGC). The *U*-value is the rate of heat loss or the energy transferred between the inner and outer of a building. It includes heat which is transferred through convection, thermal radiation (without solar radiation) and conduction. Both glazing and framing or only the center-of-glass heat loss can be expressed per time, area and temperature difference (W/m^2 K). The *g*-value is the part of solar radiation that passes through the window inside the building. Because *g*-value includes solar radiation which is absorbed and then is re-emitted, glazing surfaces have a significant impact on it. Except from these two values, transmittance in visible is another crucial factor for obvious reason.

Advanced glazing systems have been developed in order to minimize the *U*- and *g*-values of windows and contribute to the reduction of the heating and cooling loads of buildings [17–21]. Heat transfer includes different parts of electromagnetic spectrum as visible, solar and near-room-temperature infrared. Thus, a separate study for the contribution of each part in the building thermal loads is required. The solar radiation, for air mass =1.5, covers the wavelength range of 0.3–2.5 μm [11] while the thermal IR spans the region of 2.5–50 μm. The visible radiation (0.4–0.7 μm) represents about 50% of the incident solar energy, UV (0.3–0.4 μm) represents a very small amount while NIR stands for the rest 50% of the incident solar energy. Obviously, a smart control or/and solar adaptive glazing material should maximize the visible transmittance while minimize the UV and NIR parts. Reflective glazing, electrochromic and thermochromic windows, multi-pane windows, thin plastic films and double panes with air or water between them have been proposed to reduce the buildings energy needs. In these systems, the different materials developed and used are interacting with the solar radiation through the different physical mechanisms described in Fig. 1. However, the solar control strategy which is used in materials like electrochromic and thermochromic is different than the control mechanism in insulating phase change materials and results in different solar spectra (Fig. 2). Insulating materials shield the NIR radiation (or a part of it) and permit visible radiation to pass. Reflecting materials possess high reflectance for long-wave infrared radiation, low absorption of IR radiation and low emission of long-wave IR radiation. Electrochromic and thermochromic materials are developed with high visible transmittance and high IR reflectance. Recently, transparent photovoltaic materials produce electricity while permitting the visible part to be transmitted. This fascinating combination created new opportunities in windows functionality, restructured and re-shared the research directions in windows development. However, windows should not only lead to energy savings and lower buildings operating costs, but they have to esthetically fit and exhibit high durability.

In this context, the primary aim of this review is to present recent results in materials' investigation on their solar response for building integration by utilizing the reflection mechanism for controlling heat gains in the windows like the chromic materials in comparison to materials that use additional physical processes like thermal phase changes or photoelectric conversion.

Recent R&D in emerging innovative materials, insulating, reflecting, electrochromic, thermochromic, photovoltaic and water flow-based as well as their efficiency towards the maximum reduction of the solar heat gains are presented. Through the presentation of the current research trends, it is attempted to reveal the promising directions and research needs in windows' material development.