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Transmission performances of solar windows exposed to concentrated sunlight

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Abstract

To investigate the transmission performances of solar windows subjected to concentrated sunlight, an integrated sunlight transferring model was built, which was formed by a dish and a curved surface window. Considering the dish performances and the window materials, the transmissivity of the windows was predicted by the Monte Carlo ray-tracing method (MCRTM). The results show that the transmissivity of the quartz glass window is about 12.0% higher than that of the sapphire window because the refractive index and the absorption coefficient of the quartz glass is lower than that of the sapphire. For a combined dish and window system, the influences of the window geometries on the transmissivity are negligible. However, decreasing the slope errors and tracking errors of the dish is able to improve the transmission performances of the windows.

Keywords: Solar window; Transmission performance; Concentrated sunlight; MCRTM

1. Introduction

Solar windows that separate the receiver cavity from the surroundings are crucial components in high-temperature solar thermal cycles. Most volumetric solar thermal and solar thermochemical processes can be operated in the receivers equipped with the solar windows (Kribus et al., 1999; Steinfeld, 2005). From the heat transfer point of view, the solar windows not only eliminate the convection heat loss of the receiver wall, but also enable most of the incoming sunlight to enter the receiver, while trap much re-radiation (Kribus, 1994; Karni et al., 1998). As a result, windowed solar receivers can extend the application range and improve the solar thermal performances. Beside plate windows (Bertocchi et al., 2004; Roeb et al., 2006; Müller et al., 2008), many practical solar windows are manufactured as curved surface configurations to support internal receiver pressure (Wörner and Tamme, 1998; Kribus et al., 1999; Röger et al., 2005).

For the plate window, Bertocchi et al. (2004) reported the experimental evaluation of a solar particle receiver, where a plate window was fixed at the opening of the receiver. Roeb et al. (2006) investigated a solar hydrogen production by a two-step cycle based on mixed iron oxides in a windowed solar energy converter. Müller et al. (2008) carried out numerical and experimental investigation for the thermal dissociation of ZnO in a solar thermochemical reactor. A plate window was equipped at the opening of the reactor. For curved surface windows, Wörner and Tamme (1998) investigated CO2 reforming of methane in a solar driven volumetric receiver–reactor.

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Nomenclature

a	semi-major axes
b	semi-minor axes
d	thickness
x,y,z	coordinates
f	focal length
l	distance
n	refractive index
N	ray number
R_{sc}	aperture radius
R	random number
T	transmissivity
θ	incidence angle
φ	refraction angle
κ	extinction coefficient
ψ_{rim}	rim angle
ρ_w	reflectivity
σ_{slope}	slope error
σ_{track}	tracking error
σ_{cone}	half angle of the solar cone

A domed window was fixed at the opening of the receiver to support the internal pressure. Kribus et al. (1999) investigated the thermal performances of a high-temperature solar thermal receiver, where a frustum-like high-pressure (FLHiP) window was installed at the high-temperature receiver stage to form a volumetric receiver. Röger et al. (2005) investigated a multiple air jet cooling system for a solar thermal receiver window. The window was an axially symmetric part that can be approximated by a hemisphere with a cylindrical extension.

Generally, solar windows are usually made of quartz glass and sapphire due to their advantage optical, thermal, and mechanical properties. However, these subtransparent materials will reflect and absorb some incoming sunlight, resulting in reflection and absorption loss. Under certain conditions, these losses may be a major factor in determining the solar thermal conversion efficiencies. Predicting the window transmission characteristics is an important approach to investigate the solar thermal conversion performances.

During the past decades, many attempts have been made to study the transmission characteristics of the solar windows. Kribus (1994) investigated the optical performance of a conical window exposed to concentrated solar radiation by a ray tracing method. Karni et al. (1998) stated that the window equipped at the opening of the volumetric solar receiver should minimize the reflection and absorption of incoming irradiation to increase the solar thermal conversion efficiency. Shuai et al. (2011) simulated the radiative performance of a plano-convexo quartz glass window fixed at the aperture of a receiver. To increase the incoming solar intensity, Wang et al. (2013) estimated the ray transferring performances of a concave quartz window fixed at the opening of the receiver.

Apart from above investigations, attempts to minimize the reflections by coating solar selective film on the quartz glass window have started to attract attentions recently (Helsch et al., 2010; Selvakumar and Barshilia, 2012). However, common solar selective coatings is unable to operate at high temperature conditions for long time because the coating materials may be polluted by dust and burned out at high temperature state. Therefore, it will take a long time to decrease of the reflection losses by coating solar selective film for high-temperature solar cycles.

Although many investigations have been focused on the transmission performances of the solar windows, the study is still incomplete. On the one hand, the results of the previous investigations were obtained based on the hypothetical concentrated solar flux and direction distributions. In effect, the concentrated solar irradiation is extremely non-uniform in spatiality and direction. On the other hand, some references apply analytical expression to predict the transmission performances of the windows. However, the analytical expression is only available for constant-thickness plane windows. For curved surface windows the analytical expression is invalid because the local normal direction varies widely with coordinates of the points.

This paper aims to reveal the transmission characteristics of solar windows exposed to concentrated sunlight. It is arranged as follows. First, an integrated sunlight transferring model formed by a dish with a solar window was established. Second, to obtain statistical results, a great number of sunlight was traced from the dish to the solar window by a Monte Carlo ray-tracing method (MCRTM). Third, the influences of the geometries and materials of the windows on the transmission performances were discussed in detail.

2. Physical model and formulation

2.1. Physical model

Fig. 1 shows an integrated sunlight transferring model combined by a dish and a convex solar window. High pressure gas passes through the receiver to transport the concentrated solar radiation energy. To withstand internal receiver pressure, the convex surface of the window points to the receiver cavity. While the bottom surface of the convex window is placed at the focal plane of the dish. Incoming sunlight arrives at the aperture of the dish concentrator and then is focused by the dish. When the incoming sunlight strikes at the solar window, part of the sunlight is reflected, part is absorbed, and part is transmitted into the receiver cavity.