Energy Conversion and Management 105 (2015) 562–569

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Integrated analysis on the volumetric absorption characteristics and optical performance for a porous media receiver

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ARTICLE INFO

Article history:
Received 22 June 2015
Accepted 10 August 2015

Keywords:
Concentrated solar radiation
Volumetric solar receiver
Solar window
Radiative transfer
Monte Carlo ray tracing method

ABSTRACT

The absorption of concentrated solar radiation within volumetric receiver is the key step that governs the global efficiency of solar thermal systems. An integrated radiative transfer model combined the dish concentrator, solar window and porous absorber is developed. The distribution of absorbed radiation energy in the porous absorber and the optical performance of the entire system are investigated by a Monte Carlo ray tracing simulation. The detailed radiation transport within the solar window and porous absorber is fully considered. The effects of porous structure parameters, slope error of concentrator and the alignment error of receiver are analyzed. The results show that the optical losses due to the back scattering from porous absorber and the absorption and reflection of solar window have a significant influence on the optical performance of system. The porous structure parameters greatly affect the distribution of solar radiative source within the porous absorber. In addition, the optical efficiency decreases noticeably when the slope error and alignment error exist.

1. Introduction

Volumetric receiver with high-porosity material appears to be a promising technology for converting solar flux into thermal energy [1]. In the solar thermal systems, sunlight is incident on a concentrator and directed to the solar receiver. The absorbed heat within the receiver is transferred to the working fluid when it flows through the pores [2]. Due to the porosity and large extinction volume, the concentrated solar radiation penetrates deeper into the receiver causing a gradual temperature rise [3]. As one of the most important heat transfer processes in the receiver, the solar radiation transmission and absorption process is important to the overall system performance [4].

The thermal behavior and efficiency of solar receiver have been extensively investigated. The incoming concentrated solar radiation is modeled using two major approaches. In the first approach, the porous material is regarded as an optically thick medium and the heat flux at the boundary is considered as a surface phenomenon. The solar flux distribution is treated as the second boundary condition in the simulation [5]. This assumption neglects the gradual absorption characteristics of solar radiation in the receiver and cannot reflect the volumetric effect. The second approach incorporates the gradual attenuation of solar radiation within the volumetric receiver and the incident radiation is considered as a radiative heat source in the whole volume of porous absorber [6].

Using the second approach, the incident solar radiation has been treated as a collimated incident radiation beam with a uniform or Gaussian distribution in several studies [7]. In fact, the concentrated solar radiation is extremely nonuniform in spatiality and direction. This distribution has a significant impact on the temperature field in the solar receiver [8]. Therefore, the performance evaluation of solar receiver should be based on the coupling between solar flux modeling and heat transfer modeling [9]. Monte Carlo Ray Tracing (MCRT) simulations have been carried out to obtain the realistic concentrated heat flux distribution boundary conditions by some researchers. Wang et al. [10] adopted the calculated solar flux distribution on the focal plane to study the thermal performance of porous media solar thermochemical reactor. The solar radiation propagation in the reactor is calculated with the modified P1 approximation, which may break the directional distribution of the incoming solar radiation [11]. An integrated radiative transfer simulation from the solar concentrator to porous absorber is needed to effectively predict the solar energy distribution within the volumetric receiver. Several works involving the solar radiation transport have been done for solar cavity receivers, where it is radiative exchange between surfaces [12].

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http://dx.doi.org/10.1016/j.enconman.2015.08.028
0196-8904/

Only few papers focus on the direct simulation of solar radiation transport within the whole volumetric receiver. A three-dimensional optical model for a pressurized volumetric receiver (PVR) was established by Cui et al. [4] and the corresponding solar radiation transmission process was simulated with MCRT. The radiation behavior in the solar window is simplified as a constant proportion of energy absorption. The work was extended by He et al. [13] for the solar radiation propagation modeling from the heliostat field to the PVR for a solar tower power plant. Then the proposed method and code were applied to simulate and analyze the photo-thermal conversion processes in three typical collectors [14].

Furthermore, high optical losses during the process of solar energy transmission and absorption are the primary cause of low system efficiency [15]. The optical losses mainly depend on the geometry and optical properties of each component in the solar system. The solar window is used to enable high-pressure operation, minimize reflection losses, re-radiation and convection losses [16]. Since the window works under high-flux solar irradiation, under certain conditions, the reflection and absorption loss may be a major factor in determining the solar thermal conversion efficiency [17]. The radiation transport in the solar window is not fully considered in the previous investigations. In addition, although some researches have been focused on the solar radiation propagation within the solar thermal system, the study is still incomplete. This study aims to reveal the volumetric absorption characteristics of porous media receiver exposed to the highly concentrated solar radiation. An integrated model of solar radiation propagation in a concentrator-window-absorber system is established. The local solar radiative source distribution within the porous absorber and the optical efficiency of system are predicted with the MCRT method.

2. Model description

A key component in the solar thermal conversion is the receiver where the solar energy is absorbed and transformed to the working fluid as thermal energy. As shown in Fig. 1, the porous media receiver is placed vertically on the focal plane of solar dish concentrator. The incoming solar radiation is collected and redirected to the receiver. Absorption and scattering take places on the dish surface, which is considered as the optical loss of solar concentrator. Fig. 2 describes the relevant transport phenomena of solar radiation in the receiver. When the concentrated sunlight strikes at the window, part of the sunlight is reflected, part is absorbed, and part is transmitted into the receiver cavity. Then the transmitted sunlight enters the porous absorber and is absorbed or scattered in the porous media. Due to back scattering from the bulk of porous absorber, some of the sunlight may be scattered backwards to the solar window. Part of the sunlight may be absorbed by the solar window, part transmits to the surroundings through the window, and part is reflected into the porous absorber again. Besides, the reflection and absorption also occurs at the receiver wall.

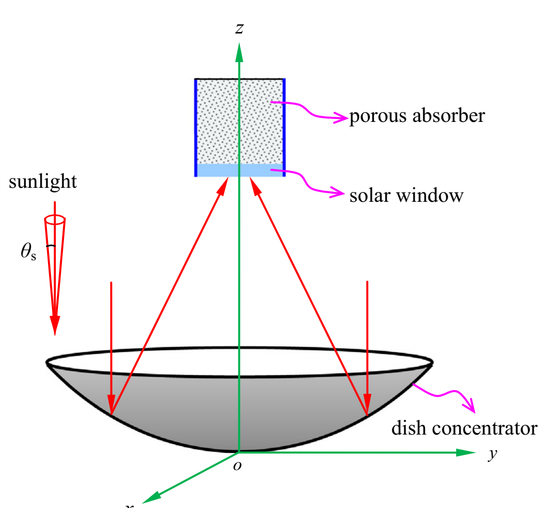

Fig. 1. Schematic of the volumetric receiver with solar dish concentrator system.

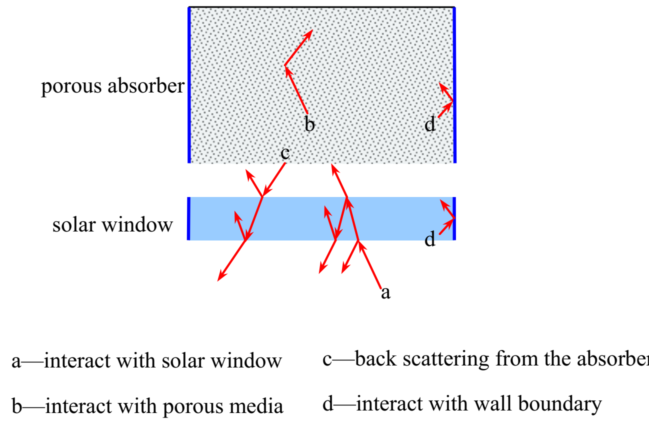

Fig. 2. Transport phenomena of the concentrated solar radiation within the receiver.

The incident radiation on the solar window is nonuniform in spatiality and direction, which is mainly determined by the concentrating performance of the dish concentrator. Furthermore, the concentrating performance depends on the geometry, optical properties and optical errors of the concentrator. In the rectangular coordinate system depicted in Fig. 1, the surface equation for the dish is

$$z = \frac{x^2 + y^2}{4f} \tag{1}$$

where f is the focal length of the dish. The optical errors may enlarge the solar image and reduce the optical performance of system [18]. For a solar concentrator, the sources of optical errors are typically a slope error σ_{slope}, a tracking error σ_{track}, non-specular reflection σ_{scatt} and some alignment error σ_{align} [19]:

$$\sigma_{opt}^2 = (2\sigma_{slope})^2 + \sigma_{track}^2 + \sigma_{scatt}^2 + \sigma_{align}^2 \tag{2}$$

In the present study, the receiver wall is assumed to be diffuse and gray. The solar window and porous absorber are both regarded as homogeneous semitransparent media in the simulation. Due to the advantageous optical and thermal properties, the quartz glass is a promising solar window material in high temperature solar thermal cycles. In addition, since most of the solar radiation spectrum falls between 0.3 and 2.75 μm, the spectrum over 2.75 μm or below 0.3 μm is negligible [17]. Thus, this wavelength range is utilized to analyze the solar radiation propagation in this study. The spectral effect of quartz solar window is taken into account and the optical property is listed in Table 1 [17]. The symbol λ denotes the wavelength, n_λ and κ_λ are the refractive index and absorption coefficient, respectively.

Table 1
Optical property of the solar window [17].

λ (μm)	n_λ	κ_λ (m^{-1})
0.3–2.6	1.42	1.4
2.6–2.75	1.45	100