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Heat transfer analysis of a volumetric solar receiver by coupling the solar radiation transport and internal heat transfer

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ABSTRACT

Volumetric receivers have become a promising technology for the solar thermal conversion. The absorption of concentrated solar radiation and the heat transfer to the working fluid are the two dominant processes. To effectively investigate the thermal performance of receiver, a numerical model coupling the solar radiation transport and the internal heat transfer is presented. Solar radiation transport from the dish concentrator to the interior of receiver is simulated with the Monte Carlo ray tracing method. Combining the distribution of absorbed solar energy in the receiver, the local thermal non-equilibrium model with P1 approximation is used to solve the internal heat transfer. Two other treatment approaches for the concentrated solar radiation are compared. One considers the solar radiation on the front surface of receiver as thermal boundary condition (TBC) and the other as a collimated incident radiation (CIR) beam. The results show that the porosity and mean cell size have a great effect on the distribution of absorbed solar radiation. Compared with the coupling approach, the TBC approach overestimates the solid temperature near the front surface with a deviation up to 76.4%, while the CIR approach provides acceptable temperature field with a deviation less than 3.4%. In addition, the fluid and solid temperatures both decrease as the slope error of concentrator increases.

1. Introduction

Volumetric receivers with high-porosity material are widely used in the solar thermal utilization, such as hydrogen production and electricity generation [1]. The concentrated solar radiation is absorbed in the receiver and the heat is transferred to the working fluid when it passes through the porous structure [2]. Due to the porosity and large extinction volume, the solar radiation penetrates deeper into the receiver causing a gradual temperature rise [3]. Therefore, the volumetric absorption of solar radiation and the internal combined heat transfer are the two dominant processes for the solar thermal conversion.

Many researches have been done to investigate the heat transfer performance of volumetric receivers. There are two major approaches to model the concentrated solar radiation on the front surface of receiver [4]. In the first approach, the heat flux at the boundary is considered as a surface phenomenon based on the assumption of very large optical thickness for the porous media. The solar flux distribution is treated as the secondary type TBC in the simulation [5]. The numerical heat transfer analyses with preferable volume convection heat transfer coefficient were carried out by Xu et al. [6]. The heat transfer analysis of a porous media receiver was conducted by Wang et al. [5] with the heat flux distribution on the fluid inlet surface calculated by the Monte Carlo ray tracing (MCRT) method. A one dimensional analysis was performed by Wang et al. [7] to study the effect of thermal radiation in porous media in the presence of local thermal non-equilibrium (LTNE) convection for a solar air receiver. The transport and global absorption of solar radiation in the receiver are not considered in the aforementioned approach, which may not reflect the volumetric effect.

The second approach incorporates the solar radiation transport within the volumetric receiver and the concentrated solar radiation is considered as a radiative heat source in the whole volume of receiver [8]. Nevertheless, instead of appropriate modeling the concentrated solar flux distribution, the impinging solar radiation on the front surface of receiver has been treated as a CIR beam with a uniform or Gaussian distribution in several studies. Using the LTNE model with P1 approximation, Wu et al. [9] simulated the temperature fields of the fluid and solid phases in a porous media receiver under Gaussian distribution. A 1 kW thermochemical solar reactor fitted with ceramic foam was studied by Villafán-Vidales et al. [8] with a Gaussian incident solar flux distribution. The impacts of variation in heat transfer model and thermophysical

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characteristics model of gas mixture on the thermal performance were investigated by Wang et al. [10] using a Gaussian distribution. Thermal performance of a volumetric solar receiver with double-layer ceramic foam is numerically studied by Chen et al. [11] with a Gaussian heat flux distribution. Most of the previous studies do not pay attention to the coupling between solar flux modeling and heat transfer modeling [12].

The absorption characteristics and heat transfer performance of volumetric receiver are mainly dependent on the concentrating system and the properties and dimensions of receiver. In fact, the concentrated solar radiation is extremely nonuniform in spatiality and direction [13]. This distribution has a strong impact on the temperature field in the receiver. However, the integrated simulation of solar radiation transport from the concentrator to the interior of receiver can be rarely found. The concentrated solar flux distribution on the front surface of solar reactor was calculated by Wang et al. [14] with MCRT, and then it was simplified as a CIR beam during the simulation of internal heat transfer. This may break the directional distribution of the incoming concentrated solar radiation. A three-dimensional optical model for a pressurized volumetric receiver (PVR) was established with MCRT by Cheng et al. [15] and the heat transfer and synthetical performance was studied, where the local thermal equilibrium (LTE) model was adopted. Then the proposed MCRT code was applied to simulate and analyze the photo-thermal conversion processes in three typical collectors [16]. A one dimensional model was presented by Kribus et al. [17] to investigate the performance of volumetric receivers as a function of geometric and material properties using the LTNE model, where the directional extent of the incident radiation was defined as a cone with opening half-angle of 45°. An integrated radiative transfer model from dish concentrator into the receiver was developed by Chen et al. [4] to analyze the optical performance of the whole system.

From the literature survey, it can be seen that the coupling between the integrated solar flux modeling and the internal heat transfer modeling has not been fully considered or comprehensively studied. In addition, the variation in structure parameters of receiver significantly affects both the input of solar flux into the receiver and the power delivered to the working fluid. The consistent modeling of the two processes is scarcely performed. In this study, a numerical model coupling the solar radiation transport from the concentrator to the interior of receiver and the internal combined radiative and convective heat transfer is developed. The corresponding solar radiation transport is simulated with MCRT, and then the solar radiative source within the receiver is incorporated into the heat transfer analysis using FLUENT with User Defined Functions (UDFs). The temperature field is predicted using the LTNE model with P1 approximation.

2. Model description

A key component in the solar thermal system is the volumetric receiver which is located at the focal plane of concentrator. As shown in Fig. 1, the solar radiation is collected and redirected to the receiver by the dish concentrator. Then, the solar radiation transmits through the window and is gradually absorbed within the porous media, which is simultaneously cooled by the forced convection of air stream. The numerical model developed in this study contains two parts: the integrated solar radiation transport and the internal heat transfer. Firstly, the solar radiation transport is fully simulated in a concentrator-window-absorber configuration with MCRT. Then the absorbed solar radiation in the receiver is coupled in the internal heat transfer analysis. The heat transfer model for numerical analysis is shown in Fig. 2, where L and R are the length and radius of porous media respectively. A local cylindrical coordinate system o-$r\varphi z$ is established for the porous media. Several assumptions are employed: (1) multi gas inlets are set, the preheating is neglected and the velocity and temperature of air flow at the inlet surface of porous media are assumed to be uniform [18], (2) the air flow is steady and incompressible, (3) the porous media is considered as a homogeneous, absorbing, emitting and isotropic scattering medium, (4) the radiative properties of all components are assumed to be gray, (5) the window effect is not included in the internal heat transfer simulation [8], and (6) lateral wall of receiver is well insulated. The geometrical and physical parameters of the concentrator and volumetric receiver are listed in Table 1.

3. Solar radiation transport simulation

MCRT method is a random simulation method based on the probability statistics and is widely used in concentrated solar research [19]. A great number of rays are traced from the concentrator to the interior of solar receiver with an in-house developed MCRT code [4]. The pillbox distribution is chosen to describe the sunshape effect, which means that the solar radiation is constant within a cone with a half angle of $\theta_s = 4.65$ mrad [20]. Besides, the value of solar radiation heat flux incident on the concentrator used in this study is $q_s = 1000\ \mathrm{W/m^2}$ [21]. The slope error σ_{slope} is applied to indicate the deviation of a real dish surface from a perfect dish surface. In MCRT process, the slope deviation can be defined by a azimuth angle φ_{se} and a zenith angle θ_{se}, which can be determined by the following expressions [22]:

$$\theta_{se} = \sqrt{\left(-2\sigma_{slope}^2\right)\ln(1 - R_{s\theta})} \tag{1}$$

$$\varphi_{se} = 2\pi R_{s\varphi} \tag{2}$$

where $R_{s\theta}$ and $R_{s\varphi}$ are random numbers which are uniformity distributed between 0 and 1.

During the ray tracing, the window and porous media are both considered as semitransparent media. Additionally, the air is transparent to the radiation. For the porous media, considering that the propagation of radiation only occurs in the transparent phase, the refractive index of porous media is generally assumed to be equal to that of the transparent phase [23]. The propagation phenomena in the porous media, scattering and absorption, are taken into account, while only the absorption characteristic of window is considered. The porous media is divided into several volume elements ($M_r \times M_\varphi \times M_z = 100 \times 60 \times 100$). Once the ray penetrates into the porous media, based on media radiation transfer theory, a possible transfer distance may be obtained from following probability expression [24]:

$$l_\beta = -\frac{1}{\beta}\ln R_\beta \tag{3}$$

where β is the extinction coefficient and R_β is a random number which ranges from 0 to 1 uniformly. When the location l_β is reached, a second random number R_ω is required to decide whether the ray is absorbed or scattered, with ω being the scattering albedo ($\omega = \sigma_s/\beta$, where σ_s is the scattering coefficient) [24]:

$$\begin{aligned} &R_\omega \leqslant \omega, \quad \text{scattering} \\ &R_\omega > \omega, \quad \text{absorption} \end{aligned}$$

If the ray is scattered, it will travel on into a new direction. Otherwise the ray is absorbed by the local element. The solar radiative source of element i caused by the concentrated solar radiation can be computed as