Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Optical and radiative properties analysis and optimization study of the gradually-varied volumetric solar receiver

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HIGHLIGHTS

- A novel design of the gradually-varied volumetric solar receiver is proposed.
- MCRT is applied to examine the porous structure reconstructed by modified random spherical bubbles method.
- Excellent optical and radiative properties are exhibited by the gradually-varied volumetric solar receiver.
- The design of porosity distribution is optimized by genetic algorithm.

ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form 14 May 2017
Accepted 26 May 2017
Available online xxxx

Keywords:
Gradually-varied volumetric solar receiver
Porous media reconstruction
Monte Carlo Ray Tracing
Optical property
Radiative property
Optimization design

ABSTRACT

The volumetric solar receiver is an important component of Concentrated Solar Power (CSP) system. In recent years, some studies concerned with the novel structures of the volumetric solar receiver have been conducted. In this paper, a gradually-varied volumetric solar receiver is proposed. The major feature of this structure is its porosity which decreases gradually from the front surface to the rear surface. Based on the modified random spherical bubbles method, a 3D computational model of this porosity-changed solar receiver is reconstructed. In addition, by combining with the Monte Carlo Ray Tracing (MCRT) method, the optical and radiative properties of this receiver are investigated. The results show that the reflection loss could be reduced owing to the lower reflectivity of this structure. It also outperforms in solar energy absorption compared with the uniform structures that are examined in this paper and exhibits a uniform solar radiative flux distribution inside the receiver. Finally, with the use of genetic algorithm, the porosity distribution of the gradually-varied volumetric solar receiver is further optimized, which leads to a much larger penetration depth of solar radiation. These results suggest that the gradually-varied porous structure provides a novel design method to enhance the solar radiation absorption and the volumetric absorption of a volumetric solar receiver.

1. Introduction

Facing with the problems of the paucity of fossil energy and the aggravation of the greenhouse effect, the use of renewable energy has drawn much attention in recent years [1–4]. Among various renewable energy technologies, Concentrated Solar Power (CSP) offers one of the major solutions to the above-mentioned problems due to the use of the unlimited resource of solar power.

As one of the important components of a CSP system, in which the solar energy is absorbed and then transferred to the heat transfer fluids, the solar receiver, especially the volumetric solar receiver has been widely studied [5,6] because of its primary advantages such as volumetric absorption, large specific surface area, and high temperature resistance [7,8].

Lots of works have been completed to investigate the properties of the volumetric solar receiver. In these studies [9–11], the so-called "volumetric effect" is defined as the existence of the ideal temperature distribution and low front surface temperature. The decreasing front surface temperature is favorable to reduce the radiation heat loss and increase thermal efficiency of the volumetric solar receiver. Meanwhile, the radiative properties of the porous media were also the major concern in researches of the volumetric solar receiver. Zhao and Tang [12] applied Monte Carlo method to determine the extinction coefficient of silicon carbide porous media and correlated the extinction coefficient with porosity and pore diameter of the sample. Parthasarathy et al. [13] used the ray tracing technique combining with the tomography-based computational structure to examine the influence of the structural

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http://dx.doi.org/10.1016/j.apenergy.2017.05.165
0306-2619/

Please cite this article in press as: Du S et al. Optical and radiative properties analysis and optimization study of the gradually-varied volumetric solar receiver. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.05.165

Nomenclature

d	pore diameter (m)
I_λ	spectral radiation intensity (W/(m^2·μm·sr))
L	total length of the porous media (m)
N	total number of sub-layer
r	pore radius (m)
(x,y,z)	Cartesian coordinates (m)
(d_x,d_y,d_z)	direction vector of numerical ray
Greek symbols	
β	extinction coefficient (m^{-1})
λ	wavelength of incident radiation (m)
ψ	constant number in correlation
ϕ	porosity

properties on the radiative properties of different porous media. Cunsolo et al. [14] developed a Monte Carlo Ray Tracing code to compare the radiative properties of the computer-generated Kelvin and Weaire-Phelan foam structures and the X-ray computed tomography reconstructed structure. Good agreement of extinction coefficient and the scattering phase function was shown of these structures.

Apart from the uniform structure, new types of receivers have also been investigated. Fend et al. [15] had put forward a double-layer silicon carbide foam which consists of a high cell density (80 PPI) in the front layer and low cell density (20 PPI) in the rear layer. The efficiency of this structure was approximately 10% higher compared to that of the uniform receiver with the cell density of 20 PPI. A similar idea could be found in the study of Chen et al. [16]. A double-layer ceramic foam was proposed and the local thermal non-equilibrium model coupled with modified P1 approximation was adopted to investigate the thermal performance. The decreasing-porosity design and the increasing-mean cell size design were highlighted owing to the achievements of higher air outlet temperature and lower radiative loss respectively. Besides, volumetric solar receiver with porosity changing in depth and in radial direction were investigated by Roldán et al. [17]. The simulation results showed that the configuration with decreasing-porosity variation (0.78–0.64–0.48) according to depth had the highest efficiency because of the deeper penetration depth and more homogeneous heat flux distribution. Moreover, the porosity-changed wire mesh absorber was experimentally investigated by Avila-Marin et al. [18]. Three configurations with different combinations of porosities (61–54%, 61–38%, and 54–38%) were examined. The experimental results pointed out that all the porosity-changed absorber presented better thermal behavior and the absorber with porosity of 54% as the first layer and porosity of 38% as the second layer showed the best performance.

In order to determine the geometrical parameters and improve the properties of new types of receivers, the intelligent method could be applied rather than conduct the parametric study manually and repeatedly. The intelligent method has been used by many researchers to optimize the structure in different applications. Zheng and He et al. [19] combined genetic algorithm and computational fluid dynamics to optimize the configuration of porous insert in a tube for heat transfer enhancement. Shi and Wang [20] showed an optimized design of transpiration cooling structures which led to the lowest temperature at the hot surface. Furthermore, multi-parameters optimization was also conducted to take total weight of structure and cost constraint into consideration. Dathathri and Balaji [21] optimized the porosity, the thickness in each porous layer, and the inlet velocity to achieve a better performance on heat transfer and pressure drop for layered porous heat sinks.

However, the new types of receivers mentioned above are actually a double-layer or triple-layer design. Between each two adjacent layers, the porosity variation changed abruptly which results in a steep change in solar radiation flux. Moreover, the radiative and optical properties were not deeply investigated which are the crucial parameters to determine the thermal performance of a volumetric solar receiver. Besides, the double-layer or triple-layer solar receivers mentioned in the previous studies had different combinations of porosities. However, no design method was proposed to support the quantitative selection of the porosities. No optimization tools were used to determine the best geometry of the absorber. As a result, an improved structure of the volumetric solar receiver needs to be further designed and a profound research is indispensable to reveal the optical and radiative properties of this novel structure.

Therefore, a gradually-varied volumetric solar receiver is proposed in this paper. A major feature of this structure is its porosity, which decreases gradually from the front surface to the rear surface. Theoretically, the higher front surface porosity maintains the above-mentioned enhanced volumetric absorption and the lower rear porosity allows more solar radiation to be trapped in the structure. The abrupt change in the interface is avoided since the porosity changes gradually. Furthermore, an optimization design method is proposed and the geometrical parameters could be selected authentically.

This paper focuses on the optical and radiative properties of this structure and makes a profound research for the design of this type of volumetric solar receiver. In part 2, the whole process to reconstruct this novel structure with a modified random spherical bubbles method is elaborated. In part 3, the basic concept and ray tracing process of the Monte Carlo Ray Tracing method are presented. In addition, the optimization algorithm (genetic algorithm) and the approach to couple this algorithm with the C++ program are presented in part 4. Finally, the optical and radiative properties of this structure are revealed and genetic algorithm is used to optimize the porosity distribution of the gradually-varied volumetric solar receiver in order to achieve a much larger penetration depth of solar radiation inside the receiver.

2. Structure reconstruction

Before studying the optical and radiative properties, the numerical model of the porous media needs to be firstly reconstructed. Many studies have been carried out by researchers to reconstruct the porous structure using mainly three different methods which could be classified as follows: Firstly, X-ray computed tomography is an effective approach to reconstruct the 3D model [22]. Normally, the spatial resolution is at the micron-scale and no damage is caused to the specimen. However, applying this technique will cost huge computational resources. Secondly, the periodic generation-based technique with the advantage of simplicity uses a unit-cell to reconstruct the 3D model. For example, the dodecahedron shape, tetrakaidecahedron shape, and cubic structure were widely used in different researches [23–25]. However, the instinct randomness of porous media is not retained. Finally, the stochastic method is favorable when randomness of the structure is required