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Performance analysis of a volumetric receiver composed of packed shaped particles with spectrally dependent emissivity

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ABSTRACT

The volumetric receiver is a key component in the concentrated power plant. In this work, we propose a novel porous medium structure for solar volumetric receivers by accounting for both high heat transfer features and low pressure drop, which is composed of packed strut cross shaped particles whose surface radiative property is spectrally dependent. A local thermal non-equilibrium model is established, and the effective parameters of the porous media are obtained from the Kelvin model. The effects of the pore size, porosity, wavelength related emissivity and Heywood circularity factor of the strut cross section on the heat transfer and flow in the receiver are investigated. Results show that the radiation loss of the receiver mainly depends on the first five representative elementary volumes. The efficiency increases with the porosity and Heywood circularity factor. By decreasing the infrared emissivity of the receiver, the efficiency increases about 3% compared to the receiver with constant emissivity. Finally, a hybrid dual layer receiver is introduced to improve the heat transfer and flow performance, and the efficiency enhancement of up to 4% can be achieved.

1. Introduction

Due to the increasing demand of energy and the challenge to control global warming and reduce the greenhouse gas emissions, the renewable power generation is being developed rapidly [1]. Among various types of renewable energies, solar energy is the most potent type because of its cleanliness and sustainability [2]. The concentrated solar power plant (CSP), as shown in Fig. 1, is a promising technology for solar energy conversion [3]. By concentrating solar flux onto the receiver, it is possible to generate high temperature steam to power the heat engine and then convert the heat energy into electricity efficiently. The solar receiver is an important component of the CSP system, which will highly affect the conversation efficiency [4]. Among all types of receivers, the volumetric receiver, which usually consists of high porosity material, can get higher operating temperature and minimize the radiation loss from the receiver [4,5]. However, the performance of volumetric receivers that have been used is not so satisfactory [5]. Because of the high temperature of the receiver, radiation dominates the heat transfer in the receiver [6]. Besides, owing to the high absorptivity of the receiver, the incident flux will be absorbed after several intersections with the porous media, as shown in Fig. 1, therefore, most of the flux will be absorbed near the front surface and cause the hot spot. In order to improve the efficiency, the front temperature of the receiver should be decreased to minimize the radiation loss and leading to the so-called "volumetric effect" [4]. Consequently, the extinction coefficient should be decreased to let more flux incident inside the receiver and the convective heat transfer coefficient should be increased to enhance the heat transfer progress, however, these two goals may not be met at the same time since there is a contradiction with the requirements. A lower extinction coefficient usually means to reduce the specific surface area (SSA), but this will also reduce the convective heat transfer coefficient. Therefore, in the receiver design, it is important to consider the compromise between these two targets. Although there are many works tried to optimize the receiver performance by changing the local geometric parameters of the receiver [7–10], the attention is mainly focused on the porosity and pore size. In fact, the strut cross section shape of the ceramic foam usually has different types [11], and the strut cross section shape has a great influence on the heat transfer and flow performance in the porous media [11–13], therefore, it is important to consider the effect of the strut cross section shape on the performance of the receiver. Besides, due to the development of the high temperature coating technology, it is now possible to apply the selective coating under high temperature condition [14–17]; thereby, the wavelength related emissivity of

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Nomenclature

ρ_s	reflectivity
ε	porosity
H	Heywood circularity factor
β	extinction coefficient (m^{-1})
k_a	absorption coefficient (m^{-1})
σ	scattering coefficient (m^{-1})
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
a	absorptivity
h_{sf}	convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
α_{sf}	specific surface area (m^{-1})
d_c	pore size (m)
C_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)

Subscripts

s	solid phase
f	fluid phase

Acronyms

BCC	Body-centered-cubic
CSP	Concentrated solar power plant
CFD	Computational fluid dynamics
DOM	Discrete ordinate method
LTNE	Local thermal non-equilibrium model
REV	Representative elementary volume
RTE	Radiative transfer equation
SSA	Specific surface area

the porous media is likely to improve the efficiency of the receiver. By involving the strut cross section shape and the spectral-dependent emissivity in the receiver design, it may help to improve the efficiency.

In order to design the highly efficient volumetric receiver, the heat transfer and flow behavior in the receiver should be thoroughly investigated. For this aim, two different strategies can be followed, i.e., the microscopic model with the exact 3D digital geometry of the porous structure and the macroscopic model with homogeneous volume, in which the porous structure characterized by its effective properties [18,19]. For the microscopic model, the digital geometry of the porous structure is usually obtained by using the idealized geometries [20–22] or the X-ray computed microtomography (μ-CT) technique [23]. Although CT technology can accurately characterize the foam structure, this technique can be costly, limiting the resolution and can only characterize a limited number of pore space samples [24]. For the idealized method, several models have been used: pentagon dodecahedron [25], Kelvin [26] and spherical voided cubic unit cells [27]. Among all these models, the Kelvin model is the most popular model and is widely used. Kopanidis et al. [21] investigated the conjugate flow and temperature fields with the Kelvin model and the results were found in reasonable agreement with the experimental measurements. Wu et al. [22] tried to discuss the convective heat transfer behavior in porous media with a Kelvin model, and a correction of the convective heat transfer coefficient has been found. Kumar et al. [28] investigated the thermophysical behavior of the open-cell Kelvin cell by using the Computational Fluid Dynamics (CFD) method. The CFD results and experimental results of the pressure drop yielded an excellent agreement. Iasiello et al. [29] investigated the thermally developing flow of air in open cell foams by using the Kelvin model and the CFD method. The heat transfer coefficients and Nusselt numbers have been obtained, and the comparison with experimental data showed a good agreement. Although the convective and conjugate heat transfer at the pore level are investigated in these works, the radiation heat transfer has not been involved since the complexity of the porous media structure makes it difficult to solve the radiative transfer equation (RTE). In the macroscopic model, the real structures of the porous material are represented by the effective parameters, which will greatly reduce the complexity of the physical problem and the cost of computations. Kribus et al. [30] investigated the performance of the volumetric receiver by using a one-dimensional model, the influence of boundary conditions, geometric parameters, spectral selectivity on the efficiency have been discussed. Shuai et al. [31] investigated a volumetric porous media solar thermochemical reactor with a macroscopic model, the results indicate that the operational parameters have a great influence on the reaction progress. Xia et al. [7] introduced a novel volumetric solar receiver with double-layer ceramic foam. The local thermal non-equilibrium model (LTNE) was adopted for energy equations. The results show the geometric properties of each porous layer have great influences on the thermal performance and pressure drop. Ho et al. [32] introduced a volumetric particle receiver with different particle release patterns to increase light trapping and heating. Results showed that the wave-like release patterns yielded greater particle temperature increases and higher thermal efficiencies than the straight-line release. The macroscopic model is used in present work due to its convenience and accuracy, however, because of the introduction of the strut shape, several effective parameters such as the effective thermal conductivity and the extinction coefficient still needed to be calculated using the idealized Kelvin model.

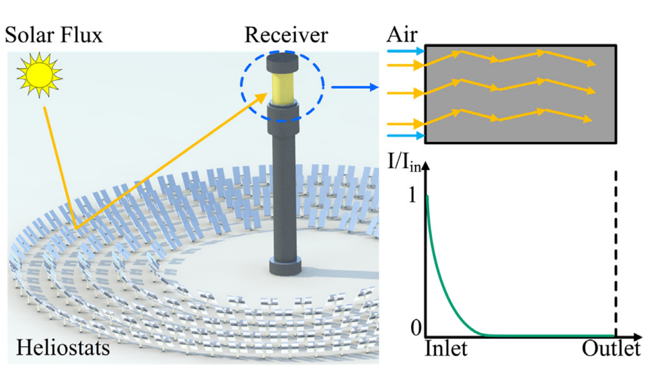

Fig. 1. Schematic diagram of the CSP and the heat flux decay process in the volumetric receiver.

In present study, the design of the receiver not only accounts for the pore size and porosity, but also takes into account the strut cross section shape and the spectral-dependent emissivity to further improve the efficiency and the flow performance. By discussing the effects of above-mentioned parameters on the receiver behavior, a general principle of designing high efficiency receivers is found. Then by properly changing the local properties of the receiver, a hybrid design receiver is introduced to achieve better efficiency and pressure drop behavior.

2. Geometrical structure and numerical model

The motivation of the present study is to discuss the effects of the extinction coefficient and the convective heat transfer coefficient on the efficiency of the receiver, and then try to obtain high heat transfer features and low pressure drop by changing the local