



Three-dimensional modelling and analysis of solar radiation absorption in porous volumetric receivers

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HIGHLIGHTS

- Convergent incidence and large pores sizes creates a peak flux near the focal point.
- Higher absorption efficiencies are obtained for forward scattering in porous media.
- The wall properties are more important in the case of low optical thicknesses.
- A even distribution and high wall absorption are obtained by moving the focal plane.
- Higher slope errors of concentrator result in lower energy absorption.

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ABSTRACT

This work addresses the three-dimensional modelling and analysis of solar radiation absorption in a porous volumetric receiver using the Monte Carlo Ray Tracing (MCRT) method. The receiver is composed of a solid matrix of homogeneous porous material and isotropic properties, bounded on its side by a cylindrical wall that is characterized through a diffuse albedo. The Henyey-Greenstein phase function is used to model the radiation scattering inside the porous media. The effect of the angle of incidence, optical thickness (porosity, pores size and height of the receiver), asymmetry factor of the phase function and wall properties on the solar radiation absorption in the porous media is studied in order to obtain the receiver efficiency as a function of these parameters. The model was validated by comparing the results for a simple geometry composed of a long slab of finite thickness with the values available in the literature, and then tested with a cylindrical receiver using a parabolic dish as concentration system with a concentration factor of 500. A peak of absorbed solar radiation of 156 MW m^{-3} and an absorption efficiency of 90.55% were obtained for a phase function asymmetry factor of 0.4 (forward scattering) and scattering albedo and extinction coefficient of 0.54 and 100 m^{-1} , respectively. The results for the diffuse reflectance, diffuse transmittance and absorption are also presented. The model developed in this work is useful to obtain and understand the energy absorption distribution in porous volumetric receivers coupled to solar concentration systems, when different porous structures and geometric parameters are used.

1. Introduction

Non-linear solar concentration systems are promising technologies to replace the conventional generation of electricity based on fossil fuels [1]. In recent years, a notable progress in concentrating solar thermal energy was achieved in terms of improving reflector designs, materials and heat transfer fluids, thermal to electric energy conversion and energy storage [2]. In these systems, two important components are the solar concentrators, which should concentrate the solar radiation on the thermal receiver, and the thermal receiver itself, where solar

radiation is converted to thermal energy. In the recent work of Ho and Iverson [3], a description of typical configurations of solar thermal receivers is made and, according to that work, the volumetric thermal receivers present great challenges from the point of view of their numerical modelling and optimization. The volumetric receivers with solid matrix (porous media) have been under investigation, mainly due to their capability to achieve high values of temperature and thermal efficiency, being one of the most promising technologies to improve the thermal efficiency of solar concentration power systems [4–7]. In the work of Ávila-Marín [8], a chronological review of volumetric receivers

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Nomenclature

A	area (m^2)
$\mathbf{a}$	arbitrary vector (–)
b	optical thickness (–)
C	concentration factor (–)
d_f	distance between the front face and the focal point (m)
d_p	pores diameter (m)
F	radiation flux at receiver front face (W m^{-2})
f	focus length (m) or fraction (–)
G_i	direct normal irradiance (W m^{-2})
g	asymmetry factor (–)
h	height (m)
L	fraction of energy lost (–)
l_β	path length of rays (m)
N	number of rays (–)
N_v	number of volume elements (cells) (–)
$\hat{\mathbf{n}}$	normal unit vector (–)
P	energy absorption in the volumetric receiver (W)
p	power per ray (W) or phase function (–)
r	radius (m)
$\mathbf{r}$	position vector (m)
S	energy absorption per unit of volume (W m^{-3})
$(\hat{\mathbf{s}}, \hat{\mathbf{v}}_D)$	unit vector direction (–)
V	volume (m^3)
W_f	fraction of energy absorbed in the wall (–)

Greek symbols

α	azimuthal angle of cylindrical coordinates system (rad)
β	extinction coefficient (m^{-1})
δ	difference
ε	emissivity (–)
η	efficiency (–)

Θ	angle of incidence (rad)
θ	polar angle (rad)
κ	absorption coefficient (m^{-1})
ξ	random number uniformly distributed between 0 and 1 (–)
ρ	reflectance of the parabolic dish (–)
σ	scattering coefficient (m^{-1})
ϕ	porosity (–)
ψ	azimuthal angle (rad)
ω	scattering albedo (–)

Subscripts

abs	absorption
cs	concentration system
dis	parabolic dish
i,j,k	indices of the volume elements (cells)
is	front face (inlet) of the receiver
os	back face (outlet) of the receiver
rec	volumetric receiver
T	total
w	receiver wall
1	initial position
2	final position

Superscripts

I	aperture area of the parabolic dish
is	front face (inlet) of the receiver
F	front face area of the volumetric receiver
os	back face (outlet) of the receiver
S	inside the receiver volume
w	receiver wall

development associated with concentrating solar power (CSP) plants is presented. The author identified the various receiver configurations, materials, power plant configurations, advantages and main problems.

In terms of modelling porous volumetric receivers associated with CSP plants, the recent work of de la Beaujardiere and Reuter [9] presents a review of performance modelling of these systems, including the energy conversion system, the thermal energy storage and the receiver modelling. Regarding the receiver modelling, two different fields of study can be identified. One of them is the absorption of solar radiation in the porous media, in which the Monte Carlo Ray Tracing (MCRT) method [6,10,11] is used, and the other one is the integration of solar radiation absorption with fluid flow and heat transfer modelling in order to obtain the thermal performance of receivers [7,12,13]. The MCRT method used to describe the light transport in biological media [14–16] can be also used to solve the problem of light transport in porous media with solid matrix [6,10,11]. In this case, there are two possible approaches: one is the computation of the propagation of ray packages with a specified statistical weight [10,11,14], in which energy absorption occurs in every interaction point and their energy decreases gradually; and the other one is the modelling of propagation of each ray, one by one, until they are absorbed or exit the system [6].

Wang et al. [14] addressed the light transport in multi-layered tissues using MCRT method and presented the results of diffuse reflectance and transmittance as function of the exit angle, which were validated with data from the work of van de Hulst [17]. Gao et al. [18] modelled and studied the effect of incidence angle, optical thickness and asymmetry factor on the diffuse reflectance of a infinite slab turbid medium. They found that for large optical thickness and small incidence angles, the angular distribution of diffuse reflectance is similar

to that of Lambertian surface. In the work of Cui et al. [10], solar radiation propagation in a pressurized volumetric receivers was modelled using the MCRT method and assuming a solar radiation flux in the front face of the receiver while a non-uniform cylindrical coordinate grid was employed in the statistical analysis of energy distribution. This technique reduces the number of cells and computation time compared to that for a uniform grid. He et al. [11] did a similar study but using a heliostat field as concentration system. In other works [10,11,14], the MCRT method was based on the propagation of ray packages while in the work of Chen et al. [6] the same method was implemented by computing the propagation of every single ray. They used a parabolic dish as the concentration system and studied the effects of porous structure parameters, slope error of the concentrator and receiver misalignment on the performance of the receiver. Zhao and Tang [19] used the MCRT method to determine the extinction coefficients of silicon carbide porous media based on the Fresnel and Beer laws in order to obtain the optical properties of the porous media. They concluded that the extinction coefficient of the silicon carbide strongly depends on the porosity and pores size. Gomez-Garcia et al. [20] modelled the radiation propagation in a porous volumetric receiver with a stack of thick square grids and also analysed the influence of geometric parameters in the receiver performance, such as the grid length and the gap between consecutive layers.

The thermal energy in the receiver is collected using a heat transfer fluid, which will transfer heat to a thermodynamic cycle that converts thermal to mechanical energy and then to electrical energy through an electric generator. Recently, Benoit et al. [21] did a review of current and future liquid, gas, supercritical, two-phase and particulate heat transfer fluids. Using air as heat transfer fluid in porous volumetric

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