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Numerical Analysis of Radiation Attenuation in Volumetric Solar Receivers Composed of a Stack of Thin Monolith Layers

Gomez-Garcia Fabrisio[a], Gonzalez-Aguilar Jose[a,]*, Tamayo-Pacheco Sergio[a], Olalde Gabriel[b], Romero Manuel[a]

[a]IMDEA Energy Institute, Ramon de la Sagra 3, 28935 Móstoles, Spain
[b]Laboratoire PROMES, UPR CNRS 8521, 7 rue du four solaire, 66120 Odeillo, France

Abstract

In a volumetric receiver installed in solar tower power plants, the absorber operates as a convective heat exchanger, absorbing concentrated solar radiation and transferring thermal energy to a fluid flowing through it. Radiation absorption is related to the absorber geometry, the optical properties of the absorber surface, and the incident radiation intensity distribution, which depends on the heliostat field configuration. In order to minimize light reflection and thermal emission from the receiver frontal surface, a well-designed volumetric absorber requires a geometry that promotes radiation penetration. In addition, it should encourage a high heat transfer to the fluid to increase the thermal efficiency of the absorber. This paper analyses the radiation attenuation in an original volumetric absorber, applying a Monte Carlo ray-tracing method. The proposed absorber consists of a stack of thin multi-channel monoliths with square cross section channels in which the relative position between consecutive layers is shifted in the transversal direction. The study includes the influence of surface optical properties (absorptivity and reflectivity), the geometrical characteristics of the structure (length, wall thickness and spacing between elements) and the incident radiation profile (related to different heliostat field configurations). As result, a general expression for describing the transmittance inside the absorber as a function of the depth length is proposed.
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Keywords: Volumetric absorber; ray-tracing; radiation attenuation; optical extinction coefficient.

1. Introduction

Solar receivers are considered one of the key technology issues to be developed in order to increase the overall solar-to-electricity performance in solar tower power plants [1]. The volumetric solar receiver concept is based on the simultaneous gradual absorption of the concentrated solar radiation inside an open medium, called absorber, and the transfer of thermal energy by forced convection from this medium to the air flowing through it. The opened nature promotes the penetration of radiation, making it possible that the absorption takes place away from the front region of the absorber. Additionally, the flow of cold air at the entrance of the absorber encourages the cooling of the irradiated external surface. The volumetric concept allows achieving higher air temperatures compared with other receiver technologies, reducing the thermal losses by re-emission at the front region. Volumetric absorbers may be metallic or ceramic; their melting point being the maximum temperature that the material can withstand (typically around 1000 ºC and 1500 ºC with metallic and

* Corresponding author. Tel.: +34-91-737-1120; fax: +34-91-737-1140.
E-mail address: jose.gonzalez@imdea.org.

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ceramics, respectively). Hence, ceramic-based materials are considered the most suitable ones to manufacture volumetric absorbers in order to reach the highest thermal efficiencies (or the highest possible air temperature).

Other studies have focused on determining the performance of ceramic structures as absorbers in volumetric receivers. Most of them concern multi-channel monoliths or honeycombs with square cross section channels [2-4] and reticulated foams [2, 3, 5-8]. Monoliths with different cross section channels [9, 10] and structural modifications [11] have also been proposed, with the goal of improving the behavior of these structures. In several works the energy balance in the absorber is determined by heat transfer equations; however, most of them assume a uniform solar radiation flux [12-14] and only few analyze the absorption of the incoming radiation inside the structure by using the Monte Carlo ray-tracing method [5, 15- 17]. Lee *et al.* carried out a numerical analysis of heat transfer on silicon-infiltrated silicon carbide (SiSiC) multi-channel absorber, including the effects of the geometrical characteristics of the structure, the material absorptivity and the incident radiation profile to determine the radiation propagation on the structure [15]. They state that even though the flux distribution emitted by a diffuse source may differ from a real solar flux distribution, it is applicable to performance evaluation on multi-channel absorbers. Additionally, they conclude that the propagation of radiation depends on the pitch size of channels rather than the material absorptivity; this means that classical multi-channel structures present an intrinsic limitation on the radiation propagation.

This study proposes an original configuration for a volumetric absorber based on a stack of thin monoliths that might make it possible to increase the penetration depth of radiation inside the structure. This absorber potentially improves heat transfer by encouraging the mixing of the air without a significant increase in pressure drop. In order to obtain the optical behavior of the proposed absorber, a numerical analysis on radiation absorption has been carried out using the Monte Carlo ray-tracing method.

Nomenclature

a	optical coefficient
d	spacing between layers (m)
d^*	dimensionless spacing between layers
e	wall thickness (m)
e^*	dimensionless wall thickness
I	flux density (W/m^2)
k	dimensionless attenuation length
L	layer length (m)
L^*	dimensionless layer length
l	pitch size (m)
P	power (W)
Greek symbols	
θ	half angle of aperture (deg)
ρ	reflectivity
Subscripts	
abs	absorbed
0	incoming
L	losses
Abbreviations	
EC	Elementary cell
Ref	Reference absorber

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