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Numerical analysis of radiation propagation in a multi-layer volumetric solar absorber composed of a stack of square grids

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Abstract

In volumetric receivers of solar tower power plants, the absorber operates as a convective heat exchanger, absorbing concentrated solar radiation and transferring thermal energy to a heat transfer fluid flowing through it. A high-performance volumetric absorber must minimize the power losses by reflection and re-emission on its frontal face, promote radiation propagation and encourage a high heat transfer to the fluid. This paper analyses the radiation propagation in an original volumetric absorber, applying the Monte Carlo ray-tracing method. The proposed absorber consists of a stack of thick square grids in which the relative position between consecutive grids is shifted in the transversal direction. This study analyses the influence of the grid length, the gap between consecutive grids and the wall thickness, the significance of the absorber reflectivity, and the effect of the direction of the incident radiation. A general expression that describes the absorption capacity of the absorber and its extinction length is obtained.

Keywords: Volumetric absorber; Multi-layer; Radiation propagation; Ray-tracing

1. Introduction

One of the most important challenges of the concentrating solar thermal power (CSTP) technology is to reduce the electricity generation cost making it competitive with respect to conventional and other renewable energy resources. One way to achieve this aim is by enhancing the solar-to-electricity conversion efficiency. In solar tower power plants, this can be done using high-performance volumetric receivers. In this technology, the concentrated solar radiation is gradually absorbed inside a porous medium or absorber while a cold air stream is propelled in the radiation propagation direction to remove the absorbed heat by convection. In this way, the highest temperature region is located inside the absorber, minimizing the heat losses by thermal re-emission.

Volumetric absorbers may be metallic or ceramic, both materials having comparable thermal conductivities (around $30\ \mathrm{W\,m^{-1}\,K^{-1}}$@1000 °C (Morgan Technical Ceramics Haldenwanger, 2007; Special Metals Corporation, 2005)). However, ceramic absorbers are able to withstand (around 1200 °C (Agrafiotis et al., 2007; Wu et al., 2011a)) higher maximum operating temperatures than metallic absorbers (around 1000 °C (Special Metals Corporation, 2005)) and therefore lead to higher solar-to-electricity conversion efficiencies.

Ceramic absorbers have been analyzed in the last three decades, mainly focused on monolithic honeycombs with square cross section channels and open-cell foams. Regarding the analysis of the radiation propagation, two

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Nomenclature

Latin characters

a	absorption capacity (–)
d	longitudinal gap (m)
E_0	incoming flux density (W m^{-2})
E_a	flux density locally absorbed (W m^{-2})
E_i	incident irradiance (W m^{-2})
e	wall thickness (m)
k	dimensionless attenuation length (–)
l	pitch size (m)
L	layer length (m)
L_s	radiance scattered (W m^{-2} sr^{-1})
m	number of impacts (–)
n	number of point sources (–)

Superscripts

*	dimensionless variables

Greek symbols

φ	spherical polar coordinate (–)
Φ	non-absorbed local flux (W)
Φ_0	incident flux (W)
$\Phi_{0,ph}$	flux of a single incident photon (W)
$\Phi_{m,ph}$	flux of a single photon after m impacts (W)
Φ_R	reflected flux (W)
γ	modified dimensionless attenuation length (–)
ρ	reflectivity (–)
θ	mid-angle of aperture (°)
ω	spherical polar coordinate (–)

Abbreviations

BSDF	bidirectional scattering distribution function
EC	elementary cell
RA1	reference absorber 1
RA2	reference absorber 2

different approaches have been considered. The first one is based on the probabilistic Monte Carlo method, in which the direction and the extinction of the solar radiation is calculated along the absorber length, whilst the second one is based on analytical models developed from experimental results. In honeycomb absorbers, the simplicity of the geometry allows the use of the Monte Carlo method (Lee et al., 2012; Sánchez-González et al., 2004). One of the few studies using this approach (Lee et al., 2012) showed that radiation propagation strongly depends on the direction of the incident rays and that 90 % of the incident radiation is absorbed along a length of 3.3 times the pitch size of the absorbers. This points out that the architecture of honeycomb limits the radiation propagation. Concerning open-cell foam absorbers, the application of the Monte Carlo method can become extremely hard due to the complexity of the structure. Therefore, the use of analytical models (e.g. Rosseland, P-1 model or two-flux approximation) that simplify the calculation of radiation propagation is a common practice (Mey et al., 2014; Wang et al., 2013; Wu et al., 2011b). The analysis of these models indicates that the radiation propagation in open-cell foam absorbers is lower than in honeycombs. In recent years, experiments and numerical simulations on multi-scale grids have shown how turbulent flow is generated in grid structures (Hurst and Vassilicos, 2007; Krogstad, 2012; Nagata et al., 2008). These results suggest that high convective heat transfer coefficients could be obtained in a volumetric absorber based on this concept.

In this context, this study proposes an original volumetric absorber and presents a numerical analysis, based on the Monte Carlo ray-tracing method, which evaluates the radiative performance of the absorber in terms of absorption capacity and extinction length. Section 2 describes the proposed absorber and the physical domain in which radiative analysis was performed. Section 3 defines the light source used for modelling the concentrating solar light beam, the radiative properties of the materials and the software tools. Main results will be presented and discussed in Section 4.

2. Analyzed absorber configurations

2.1. Multi-layer absorber

Fig. 1 shows the proposed absorber structure. It is formed by a stack of thick square grids with a length L. Consecutive grids are shifted in the transversal direction (y- and z-axis) by a distance $(l + e)/2$, where l and e are the pitch size of the channels and the wall thickness, respectively. Moreover, grids are separated in the longitudinal direction (x-axis) by a constant gap d. In this architecture,

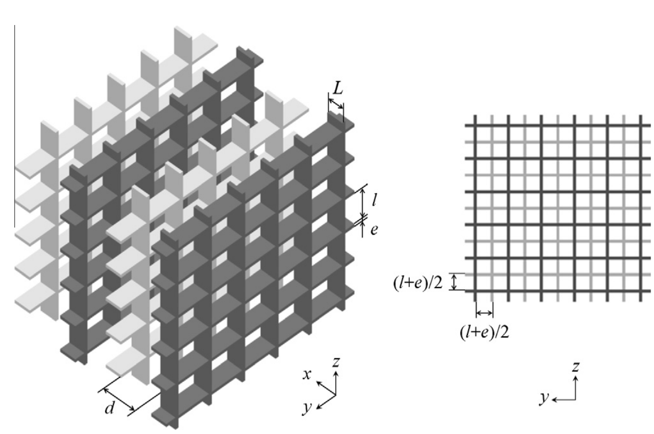

Fig. 1. Scheme of the proposed configuration of the multi-layer absorber.