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Radiative analysis in a multichanneled monolith solar reactor coated with $ZnFe_2O_4$ thin film

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ABSTRACT

The numerical evaluation of the radiative heat transfer in a multichanneled solar reactor coated with $ZnFe_2O_4$ thin-film is performed by using a channel-level simulation. A ray-tracing simulation of a 25 kW solar furnace allows obtaining the radiation distribution at each channel aperture. Then a Monte Carlo ray tracing is performed to analyze the radiative heat transfer on the monolith to optimize the channel-level geometry and film thickness for maximum absorptance and more homogeneous temperature distributions. The model considers the optical properties of $ZnFe_2O_4$ films deposited on zirconia substrate, obtained through the characteristic matrix method. This approach allows accounting for important reactor design parameters and operational conditions, such as $ZnFe_2O_4$ layer thickness, incoming radiation profile, diameter and length of pores and position of the monolith in the focal zone of the solar furnace.

1. Introduction

Solar-driven thermochemical processes constitute a promising route to obtain hydrogen or syngas, due to high overall efficiencies [1]. Thermochemical processes comprise five routes [2], however, emission-free routes, such as two-step thermochemical cycles based on metal oxides, are of particular interest since they produce pure hydrogen or syngas without using fossil fuels. In these cycles, the metal oxides are first reduced at high temperatures ($T > 1200\ K$) releasing oxygen. In the subsequent step, reduced phase is then oxidized back at lower temperatures in the presence of H_2O or a mixture of H_2O/CO_2 to produce pure hydrogen or syngas, respectively [3].

To perform both steps, solar thermochemical cycles require reactors capable to operate at high temperatures and under highly concentrated solar energy. In the last years, numerous solar reactor concepts have been proposed for demonstrating the viability of these routes [4]; nevertheless, those that exhibit volumetric absorption of radiation inside it, such as reactors based on porous media, are of particular interest since its configuration avoids the transport of solids, simplifying the reactor thermal behavior and performance of the process [5–7]. The above is because porous absorbers allow the propagation of concentrated radiation within its structure, and thus obtaining maximum temperatures inside the porous media (know as ”volumetric effect”) [8,9]. Among the different types of porous absorbers, those with well defined patterns, such as monolithic honeycombs or multichannel structures, can be optimized with simplified procedures, as compared to foam-like structures (which have non-structured cells with different shapes and sizes). The majority of optimization studies consider models that use volume-average governing equations, which are convenient for engineering applications because the complexity of the problem and computational time are reduced [7,10–20]. However, radiative transport phenomena in porous media largely depend on the morphology of the porous media [8]. Thus, is necessary to develop methods that allow modeling the effect of the morphology on the different phenomena [21,22]. Many previous studies have been devoted to predict radiative properties [21,23–27] or to understand the effect of the monolith geometric parameters on the receptor performance [5,19,21,24,28–31]. Some of these models simplified incident radiation by assuming uniform heat generation and collimated or diffuse light incidence [5,21,32]. Other studies performed a MC ray tracing in a solar concentrator [24,28]. However, none of the previous studies takes into account the optical properties of reactive coating radiative effects along with a detailed description of the incident solar radiation, which could highly impact on the reactor performance.

In the present study, a radiative heat transfer model is developed for $ZnFe_2O_4$ thin-films supported on a multi-channeled zirconia monolith.

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Nomenclature

$\bar{x}$	x axis of the local coordinate system
$\bar{y}$	y axis of the local coordinate system
$\bar{z}$	z axis of the local coordinate system
ΔS	Differential surface area, [m^2]
$\hat{i}$	Normal vector for the incident rays[dimensionless]
$\hat{n}$	Surface normal vector [dimensionless]
$\hat{r}$	Normal vector for reflected rays, [dimensionless]
A_{pt}	Element surface area, [m^2]
A_{ij}	Element *ij* of auxiliary matrix[WK^{-4}]
D_{ij}	Fraction of absorbed radiation in the element surface *j* emitted from the element *i*, [dimensionless]
E_{ii}	Radiant power of individual ray *ii*[W]
F	Solar flux distribution, [dimensionless]
f_{ii}	Normalized solar flux[dimensionless]
G	Global error distribution[dimensionless]
G_b	DNI solar radiation, [Wm^{-2}]
H	Channel lenght [mm]
K	Extinction coefficient, [dimensionless]
k_0	Wave number, [m^{-1}]
M	Characteristic matrix of a single layer, [dimensionless]
M'	Characteristic matrix of a multilayer, [dimensionless]
m'_{jk}	Complex component *jk* of the matrix M', [dimensionless]
N	Refraction index, [dimensionless]
n_c	Complex index of refraction of the material, [dimensionless]
P_{0j}	The amount of incident radiation incoming from the concentrator and absorbed in the element surface *j*, [W]
R	Channels radial position [mm]
T	Temperature[K]
r_s	Propagation direction of each ray, [dimensionless]

Chemical compounds

H_2O	Water
$ZnFe_2O_4$	Zinc Ferrite
ZrO_2	Zirconia

Greek letters

A	Absorbance, [dimensionless]
Δ	Mixed metal oxide layer thickness, [nm]
ε	Emisivity, [dimensionless]
λ	Wavelength, [μm]
ϕ	Incidence angle, [radians]
ρ	Reflectance, [dimensionless]
ρ_a	Radial angle for conical distributions, [radians]
Σ	Stefan-Boltzmann constant, [$5.67037321 \times 10^{-8} Wm^{-2}K^{-4}$]
σ_e	Standard deviation, [dimensionless]
T	Transmittance, [dimensionless]

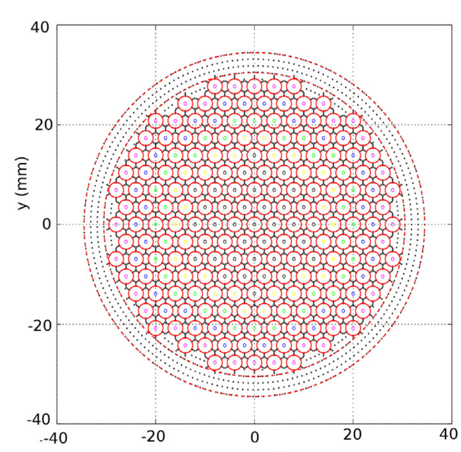
The model considers the directional characteristics of incoming solar radiation and radiative phenomena such as reflection, absorption, emission, and interference on the monolith internal and external surfaces. The description of the optical response of the supported $ZnFe_2O_4$ film is obtained by the characteristic matrix method (CM) [33], and the incoming radiation distribution model is derived from a rigorous ray-tracing simulation of the IER-UNAM solar furnace [34]. The radiative model is then used to analyze the effect of changing the monolith geometric parameters, such as metal oxide thin-film thickness and monolith channel diameter, and length on temperature distributions. This allows finding parameter ranges that maximize and homogenize radiation absorption.

2. Problem statement

The simulated porous media consists of a 64 mm-diameter zirconia cylindrical volume composed of 199 small channels of 3 mm-diameter and 15 mm-length (Fig. 1a). Fig. 1b shows the computational reconstruction of the real porous media (Fig. 1a), which is used for simulations. This reconstruction considers 3 mm-diameter channels, 1 mm-gap between channels and 64 mm-diameter by 15-mm length monolith. Channel generation on (Fig. 1b) stops at 4 mm from the monolith edge there by generating a total of 199 channels.

Due to the monolith internal geometry the radiative exchange in each channel can be solved independently. Hence, the proposed model exploits this by solving one channel temperature profile independently. Different channels can be modeled simply by changing its location relative to the monolith. The front aperture of channels is exposed to concentrated solar energy provided by a solar furnace. The modeled solar furnace is the IER-UNAM high-radiative flux solar furnace facility located in Temixco, Mexico. This solar furnace consist of an arrangement of 409 hexagonal-shape, spherical facets placed on a spherical structure. The experimental measured radiative power of the furnace is 25 kW, with peak concentrations of about 18,000 suns

(a)



(b)

Fig. 1. Geometry used in the model. (a) Photograph of the porous media, (b) computational reconstruction of the porous media.