Development and validation of a 3D CFD model for simulation of porous volumetric receivers in solar concentration systems

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Contents

Concentrated Solar Power (CSP) plant

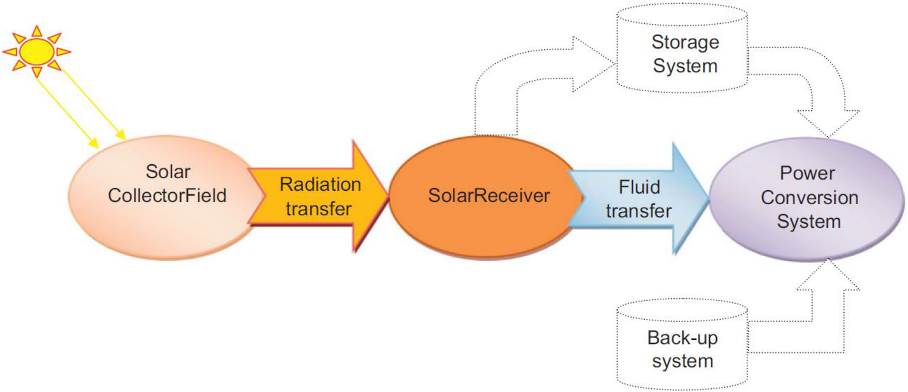

Figure 1: Flow diagram of a typical CSP plant [1]

Types of high-temperature solar central receivers [2]

- Gas receivers (**porous volumetric receiver**, suspended submicron particles and tubular);
- Liquid receivers (tubular and falling-film);
- Solid particle receivers.

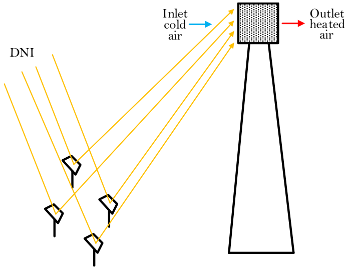

Figure 2: Tower type

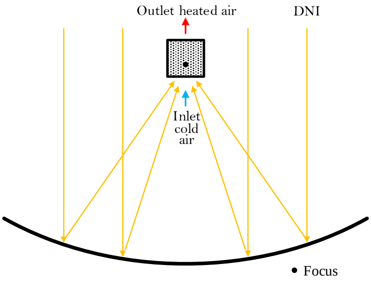

Figure 3: Parabolic dish type

Examples of porous volumetric receivers

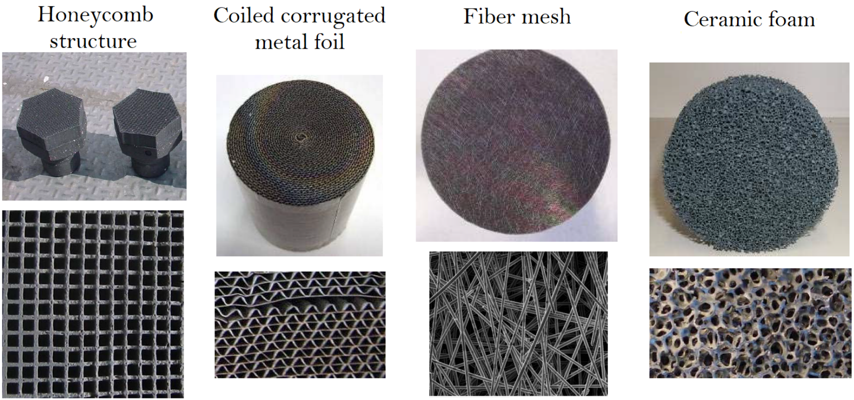

Figure 4: Four different matrix absorbers [3]

Basic concept and advantages of porous volumetric receivers

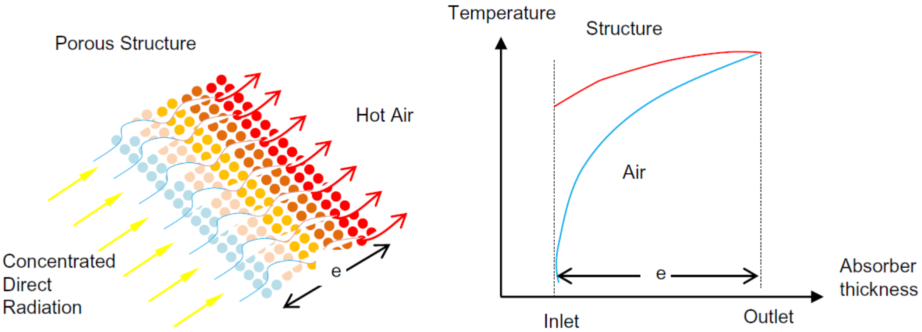

Figure 5: Basic concept of porous volumetric receiver [1]

Objectives

- Model development and validation of the solar radiation absorption, fluid flow and heat transfer processes in the porous volumetric receiver;
- Contribute to maximize the thermal efficiency;
- Contribute to increase the durability and stability of materials;
- Providing answers to current challenges in porous volumetric receivers optimization.

Physical model

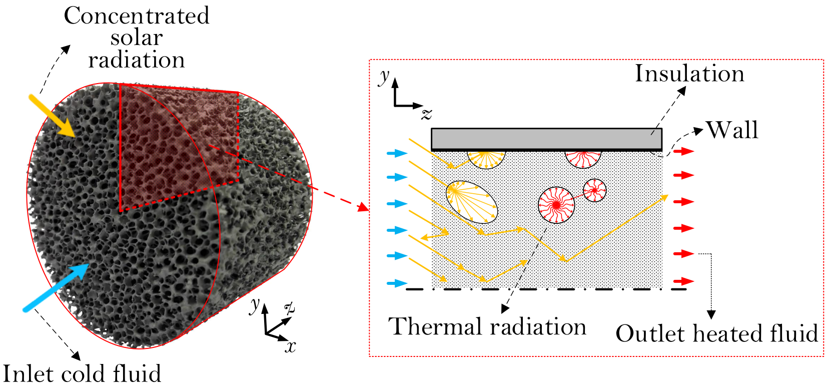

Figure 6: Fluid flow and heat transfer processes in a porous volumetric receiver element

Numerical modelling

Most relevant assumptions in the first approach

- Ceramic foam;
- The pores are spherical;
- The porous media is homogeneous and isotropic;
- The parabolic dish is considered as the solar concentration system.

Numerical modelling

Solar radiation absorption modelling (Monte Carlo ray tracing method)

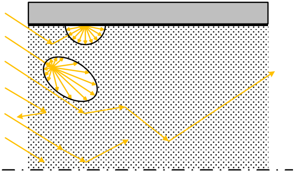

Figure 7: Porous media

Path length of rays, $l_\beta = -\frac{1}{\beta}\ln\xi$

Albedo, $\omega = \frac{\kappa_s}{\beta}$

$\xi \leq \omega$, scattering

$\xi > \omega$, absorption

Henyey-Greenstein phase function [4]

$$p(\theta) = \frac{1}{4\pi}\frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}}$$

Numerical modelling

Fluid flow and heat transfer modelling (CFD)

- Continuity equation

$$\nabla \cdot (\rho_f \vec{U}) = 0$$

- Momentum equation

$$\frac{1}{\phi}\nabla\left(\rho_f \frac{\vec{U}\cdot\vec{U}}{\phi}\right) = -\nabla p + \nabla \cdot \left(\frac{\mu_f}{\phi}\nabla \vec{U}\right) + \vec{M}_s$$

- Energy equation
  - Heat transfer fluid

$$\nabla \cdot \left(\rho_f c_p \vec{U} T_f\right) = \nabla \cdot (\lambda_{fe} \nabla T_f) + h_v (T_s - T_f)$$

  - Solid matrix structure

$$0 = \nabla \cdot (\lambda_{se} \nabla T_s) + h_v (T_f - T_s) + Q_{solar} + Q_{ir}$$

$$\begin{cases} Q_{ir} = -\kappa_a \left(4\,\sigma\, T_s^4 - G\right) \\ -\nabla \cdot \left(\dfrac{1}{3\,(\kappa_a + \kappa_s)}\nabla G\right) = \kappa_a \left(4\,\sigma\, T_s^4 - G\right) \end{cases}$$

Numerical modelling

Solution method (MCRT and CFD)

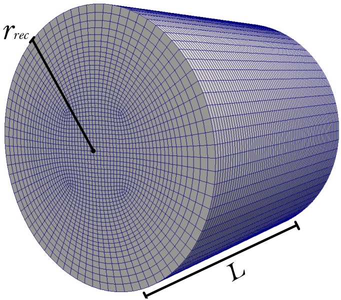

Figure 8: CFD mesh for the simulation of porous volumetric receiver

OpenFOAM

The Open Source CFD Toolbox

Numerical modelling

Results

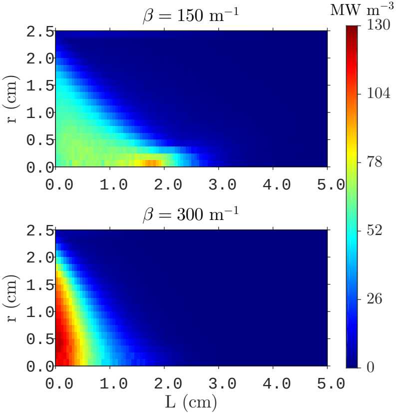

Figure 9: Effect of β on Q_{solar} [5]

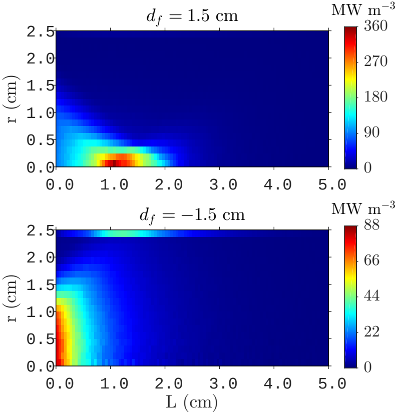

Figure 10: Effect of d_f on Q_{solar} [5]

Numerical modelling

Results

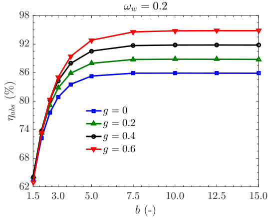

Figure 11: Absorption efficiency [5]

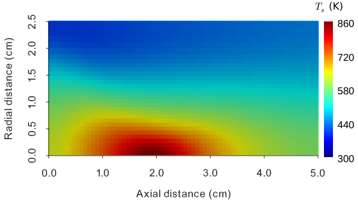

Figure 13: Solid phase temperature (T_s)

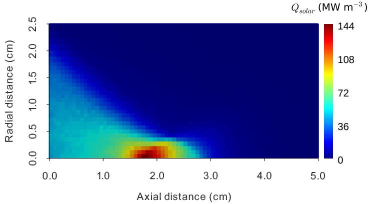

Figure 12: Absorbed solar radiation (Q_{solar}) [5]

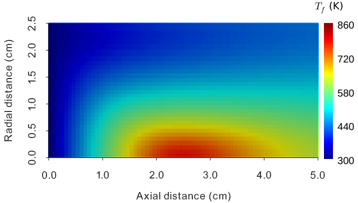

Figure 14: Fluid phase temperature (T_f)

Experimental work

Validation of the solar radiation absorption

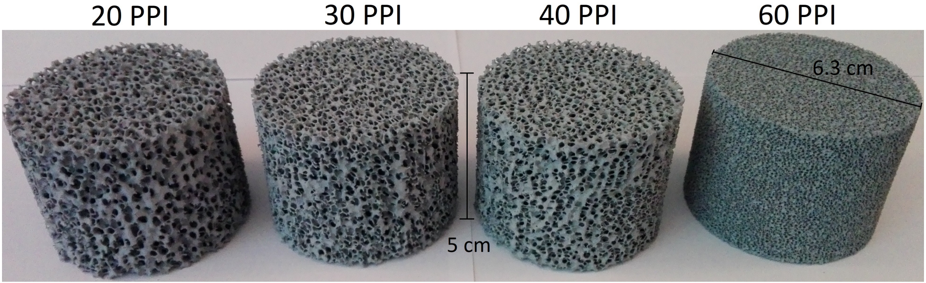

Figure 15: Samples for the experimental work (Provided by LANIK foam ceramics [6])

PPI $\Rightarrow$ pores per inch

Experimental work

Validation of the solar radiation absorption (under progress)

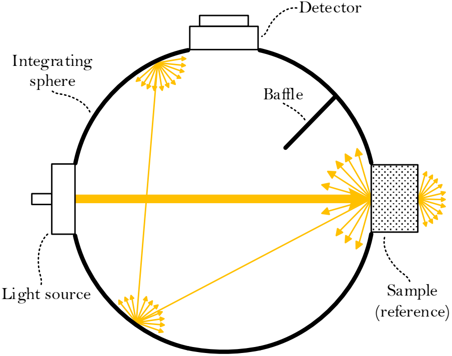

Figure 16: Experimental procedure

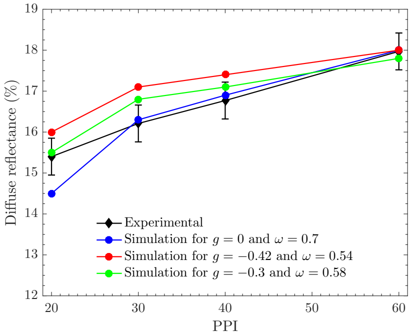

Figure 17: Experimental

- Experimental validation (Fluid flow and heat transfer);
- Modelling using different concentration systems (Tower type concentrators);
- Optimization of geometric parameters and fluid flow conditions.

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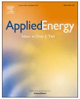

Three-dimensional modelling and analysis of solar radiation absorption in porous volumetric receivers

Check for updates

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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.

Three-dimensional CFD modelling and thermal performance analysis of porous volumetric receivers coupled to solar concentration systems

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Abstract

Porous volumetric receivers is a promising technology to improve the thermal performance of a new generation of concentrated solar power (CSP) plants. In this sense, this work addresses the Computational Fluid Dynamics (CFD) modelling and thermal performance analysis of porous volumetric receivers coupled to solar concentration systems. A cylindrical receiver element made of open-cell SiC ceramic foam was considered. The fluid flow and heat transfer processes in the porous media are modelled through volume averaged mass, momentum and energy conservation equations, considering the local thermal non-equilibrium (LTNE) approach, while the thermal radiation transfer is described by the P1 spherical harmonics method, using an open source software (OpenFOAM). An in-house algorithm based on the Monte Carlo Ray Tracing (MCRT) method was developed and coupled to the CFD mesh to model the propagation and absorption of solar radiation. The modelling of the receiver boundary conditions were improved, and a detailed analysis of a reference configuration of the receiver was conducted using a parabolic dish with a concentration ratio of 500 to generate the concentrated solar radiation field and a receiver element with diameter 5 cm, height 5 cm, pore size 3 mm and porosity 0.9. The thermal power output,

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References

[1] Omar Behar, Abdallah Khellaf, and Kamal Mohammedi.
A review of studies on central receiver solar thermal power plants.
Renew. Sustain. Energy Rev., 23:12–39, 2013.

[2] Clifford K. Ho and Brian D. Iverson.
Review of high-temperature central receiver designs for concentrating solar power.
Renew Sust Energ Rev, 29:835–846, 2014.

[3] Thomas Fend.
Characterization of Advanced Solar Air Receiver Materials, 2012.

[4] L. G. Heney and J. L. Greenstein.
Diffuse radiation in the Galaxy.
Astrophys, J. 93:70–83, 1940.

[5] Germilly Barreto, Paulo Canhoto, and Manuel Collares-Pereira.
Three-dimensional modelling and analysis of solar radiation absorption in porous volumetric receivers.
Appl Energy, 215:602–614, 2018.

[6] LANIK foam ceramics.
`http://www.lanik.eu/en`.