OPENFOAM SOLVER FOR 3D MODELLING OF SOLAR THERMAL VOLUMETRIC RECEIVERS COUPLED TO CONCENTRATION SYSTEMS

GERMILLY BARRETO[1], PAULO CANHOTO[2], MANUEL COLLARES-PEREIRA[3]

[1] *Instituto de Ciências da Terra (ICT), Universidade de Évora, germilly@uevora.pt*

[2] *Departamento de Física e Instituto de Ciências da Terra (ICT), Universidade de Évora, canhoto@uevora.pt*

[3] *Cátedra Energias Renováveis, Universidade de Évora, collarespereira@uevora.pt*

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Over the last few years, the use of porous volumetric receivers in concentrated solar power (CSP) plants is being extensively investigated. In this work, a three-dimensional solver is developed in OpenFOAM to model the solar radiation absorption, thermal and hydrodynamic performance of porous volumetric receivers coupled to solar concentration systems. The porous structure is assimilated to a continuous semi-transparent medium, and the volume averaged mass, momentum and energy conservation equations are solved using the local thermal non-equilibrium (LTNE) approach [1]. The absorbed solar radiation in the solid matrix structure is modelled by coupling a 3D in-house algorithm based on the Monte Carlo Ray Tracing (MCRT) method [2] with the CFD mesh, while the thermal radiation transfer is described by P1 spherical harmonics method. To test the model, a cylindrical receiver element (5 cm of diameter and 5 cm of height) made of open-cell SiC ceramic foam coupled to a parabolic dish with a concentration ratio of 500 is considered. The global model (MCRT and CFD) is designed to have as input the concentrated solar radiation and angle of incidence fields at the receiver inlet, and the main results are the spatial distributions of the absorbed solar radiation, temperature of the fluid and solid matrix structure and fluid velocity. The thermal efficiency, mean fluid temperature at the outlet and pressure drop across the receiver for the test conditions are 85.46%, 474.22 K and 103.10 Pa, respectively. The solver can be easily adapted to model the performance of porous volumetric receivers in different CSP systems.

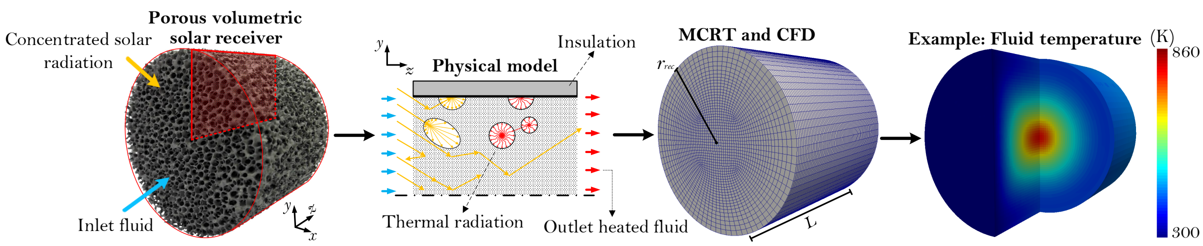

Figure 1: Solar radiation absorption and CFD modelling of porous volumetric receivers in CSP plants

Acknowledgments

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[2] G. Barreto, P. Canhoto, and M. Collares-Pereira, "Three-dimensional modelling and analysis of solar radiation absorption in porous volumetric re-ceivers," *Applied Energy*, vol. 215, pp. 602–614, 2018.

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Contents

Porous structure as solar thermal receivers

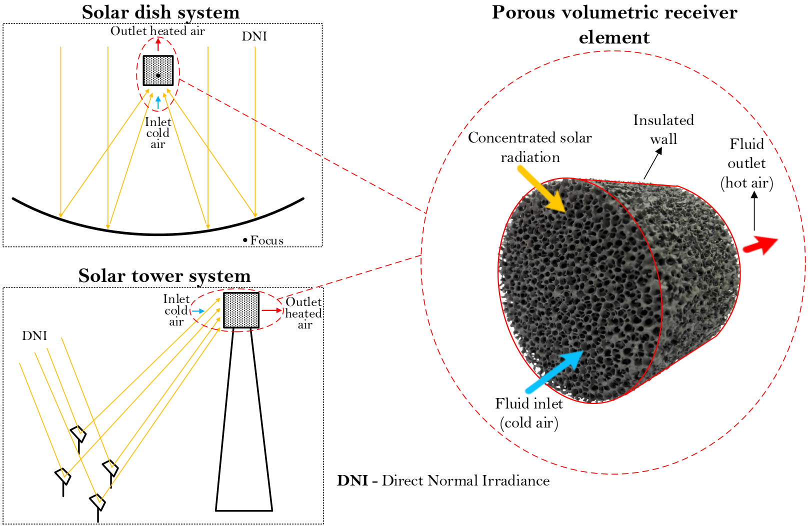


Figure 1: Porous volumetric receivers in concentrated solar power (CSP) systems

Physical model

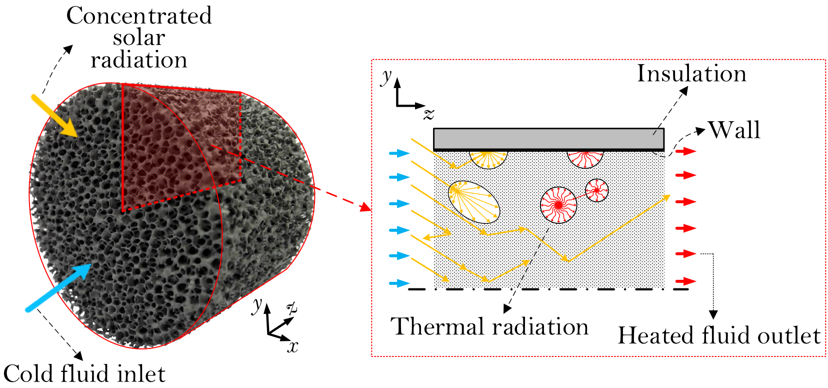


Figure 2: Fluid flow and heat transfer processes in a porous volumetric receiver element

Solar radiation absorption (Monte Carlo ray tracing method)

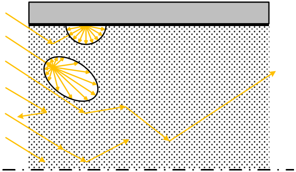


Figure 3: Solar radiation transport and absorption in the porous structure of the thermal receiver

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

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

$\xi \leq \omega$, scattering

$\xi > \omega$, absorption

β – extinction coefficient
κ_s – scattering coefficient
ω – single scattering albedo
ξ – random number

Henyey-Greenstein phase function [1]

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

g – asymmetry factor θ – scattering angle

Fluid flow and heat transfer (Steady state conditions)

- 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

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

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

Boundary conditions

- Inlet ($z = 0$):

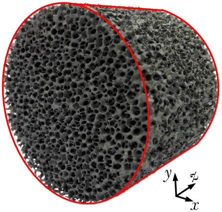
$$\vec{U} = \vec{U}_{in}$$
$$\vec{n} \cdot \nabla p = 0$$
$$T_f = T_{in}$$
$$(1-\phi)\lambda_s(\vec{n} \cdot \nabla T_s) + (1-\phi)\varepsilon\sigma(T_s^4 - T_{in}^4) = 0$$
$$\frac{1}{2}(4\sigma T_{in}^4 - G) = \frac{1}{3\beta}\vec{n} \cdot \nabla G$$

- Outlet ($z = L$):

$$\vec{n} \cdot \nabla(\vec{U} \cdot \vec{n}) = 0$$
$$p = p_{out}$$
$$\vec{n} \cdot \nabla T_f = 0$$
$$(1-\phi)\lambda_s(\vec{n} \cdot \nabla T_s) + (1-\phi)\varepsilon\sigma(T_s^4 - \overline{T}_f^4) = 0$$
$$\frac{1}{2}(4\sigma \overline{T}_f^4 - G) = \frac{1}{3\beta}\vec{n} \cdot \nabla G$$

- Wall:

$$\vec{U} = \vec{0}$$
$$\vec{n} \cdot \nabla p = 0$$
$$T_f = T_s$$
$$(1-\phi)\lambda_s(\vec{n} \cdot \nabla T_s) + \phi\lambda_f(\vec{n} \cdot \nabla T_f) = 0$$
$$\frac{\varepsilon_w}{2(2-\varepsilon_w)}(4\sigma T_s^4 - G) = \frac{1}{3\beta}\vec{n} \cdot \nabla G$$



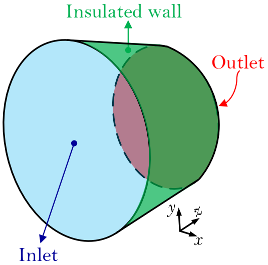
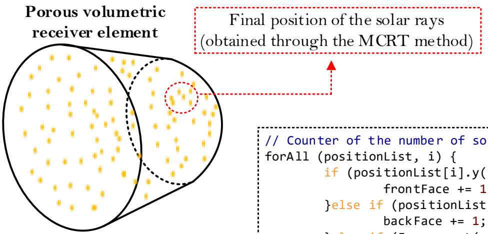


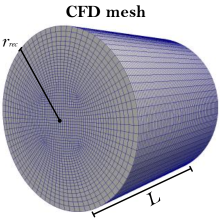
Figure 4: Boundary patch of the porous volumetric receiver element

OpenFOAM coding



OpenFOAM

The Open Source CFD Toolbox




```
// Counter of the number of solar rays inside each cell of the CFD mesh
forAll (positionList, i) {
        if (positionList[i].y() < 0) {
                frontFace += 1;
        }else if (positionList[i].y() >= hMax) {
                backFace += 1;
        }else if (Foam::sqrt(pow(positionList[i].x(), 2)
                        + pow(positionList[i].z(), 2)) >= rMax) {
                        positionParede.append(positionList[i]);
        }else {
                cellID = mesh.findCell (positionList[i]);
                if (cellID == -1) {
                        positionBetweenParede.append(positionList[i]);
                        cellID = mesh.findNearestCell(positionList[i]);
                }
                cellsCounted[cellID] += 1;
        }
}
```

$$Q_{solar} = \frac{N_{ev} e}{V_{ev}}$$

Figure 5: OpenFOAM code to obtain the distribution of absorbed solar radiation

OpenFOAM coding

```
// Define the energy conservation equation for the fluid
fvScalarMatrix TfEqn
(
     fvc::div(phi, hef) - fvm::laplacian(kfe, Tf)
   - hconv*Ts + fvm::Sp(hconv, Tf)
);
```

```
// Define the energy conservation equation for the solid
fvScalarMatrix TsEqn
(
     fvm::laplacian(kse, Ts)
   + hconv*Tf - fvm::Sp(hconv, Ts) + solarFluxRun
   + radiation->Ru() - radiation->Rp()*pow(Ts, 4.0)
);
```

Q_{solar} from the MCRT method

case/0/solarFluxRun

```
// Define the equation for U
tmp<fvVectorMatrix> UEqn
(
     (1.0/por)*fvm::div(phi/por, U)
   - fvm::laplacian(muf/por, U)
   + fvm::Sp((1039-1002*por)*muf/sqr(dp), U)
   + fvm::Sp(0.5138*pow(por,-5.739)*rho*mag(U)/dp, U)
);

// Solve the momentum predictor
Solve(UEqn() == -fvc::grad(p));
```

Momentum source

OpenFOAM

The Open Source CFD Toolbox

CFD mesh

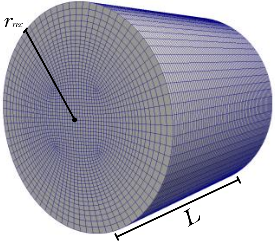


Figure 6: OpenFOAM code for fluid flow and heat transfer modelling

Model validation and testing

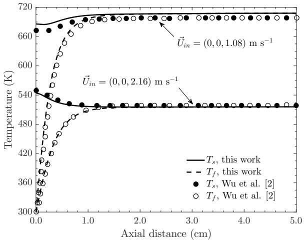


Figure 7: Comparison with other works [2]

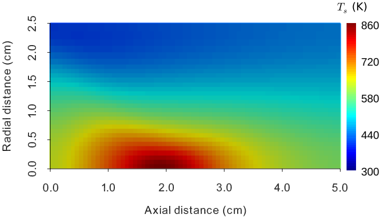


Figure 9: Solid phase temperature (T_s)

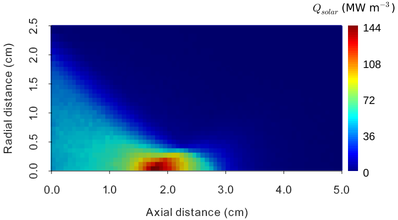


Figure 8: Absorbed solar radiation (Q_{solar}) [3]

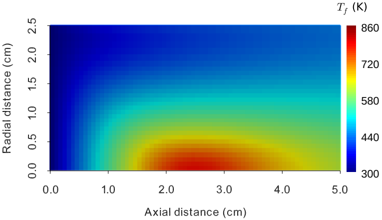


Figure 10: Fluid phase temperature (T_f)

Effect of porosity on the spatial distribution of temperature

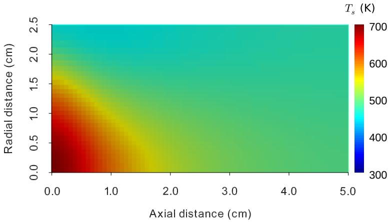


Figure 11: T_s for $\phi = 0.7$

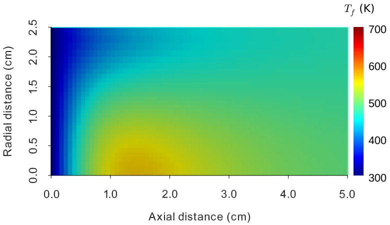


Figure 13: T_f for $\phi = 0.7$

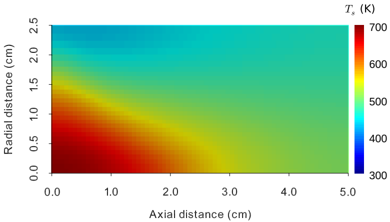


Figure 12: T_s for $\phi = 0.8$

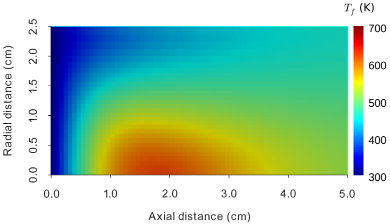


Figure 14: T_f for $\phi = 0.8$

Effect of pores size on the spatial distribution of temperature

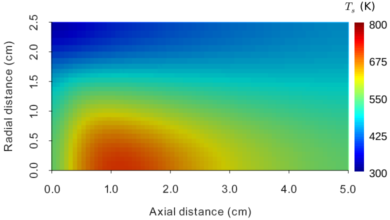


Figure 15: T_s for $d_p = 1$ mm

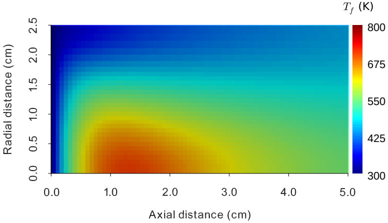


Figure 17: T_f for $d_p = 1$ mm

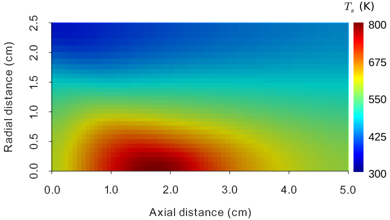


Figure 16: T_s for $d_p = 2$ mm

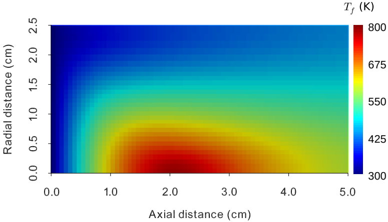


Figure 18: T_f for $d_p = 2$ mm

- Add the MCRT method to the OpenFOAM solver;
- Experimental validation (under progress);
- Use different concentration systems (e.g. tower type concentrators);
- Optimization of geometric parameters and fluid flow conditions.

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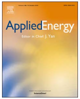

Three-dimensional modelling and analysis of solar radiation absorption in porous volumetric receivers

Germilly Barreto[a,*], Paulo Canhoto[a,b], Manuel Collares-Pereira[a,c]

[a] Instituto de Ciências da Terra, Universidade de Évora, Rua Romão Ramalho 59, 7000-671 Évora, Portugal
[b] Departamento de Física, Escola de Ciências e Tecnologia, Universidade de Évora, Rua Romão Ramalho 59, 7000-671 Évora, Portugal
[c] Cátedra Energias Renováveis, Universidade de Évora, Largo Marquês de Marialva, 7002-554 Évora, Portugal

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.

ARTICLE INFO

Keywords:
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Solar concentration
Volumetric receiver
Porous media
Monte Carlo ray tracing

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.

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

Germilly Barreto[a,*], Paulo Canhoto[a,b], Manuel Collares-Pereira[a,c]

[a] *Instituto de Ciências da Terra, Universidade de Évora, Rua Romão Ramalho 59, 7000-671, Évora, Portugal*
[b] *Departamento de Física, Escola de Ciências e Tecnologia, Universidade de Évora, Rua Romão Ramalho 59, 7000-671, Évora, Portugal*
[c] *Cátedra Energias Renováveis, Universidade de Évora, Largo Marquês de Marialva, 7002-554, Évora, Portugal*

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,

*Corresponding author
Email address: germilly@uevora.pt (Germilly Barreto)

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