Effect of thickness on the thermo-hydraulic performance of porous volumetric solar receivers with different internal geometries

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Abstract. In this work, the effect of thickness on the thermal and hydrodynamic performance of porous volumetric solar receivers made of open-cell silicon carbide (SiC) ceramic foam is investigated using an in-house detailed numerical model. The model is based in a Computational Fluid Dynamics (CFD) technique to solve the volume averaged mass, momentum and energy conservation equations, including the exchange of thermal radiation inside the receiver. A Monte Carlo Ray Tracing (MCRT) method was developed and then used to model the solar radiation transport in the porous media. Two optimised internal geometries (porosity and pores size) of the receiver with adiabatic side-walls are investigated for different thicknesses. Results show that the optimal thickness depends on the porosity and pores size and there is a value from which the thermal efficiency is nearly constant and the pressure drop always increase. It was also found that the thickness should be approximately between 5 and 7 cm for porosity and pores diameter between 0.85 and 0.90 and 3.0 mm and 4.5 mm, respectively, aiming to maximise thermal efficiency by decreasing the transmission losses of solar radiation, and to keep low pressure drop.

1. Introduction

Porous volumetric receivers are nowadays one of the most promising technology of solar thermal receivers. This is mainly due to their great potential to achieve high temperatures and to increase the efficiency of concentrated solar power (CSP) plants [1]. Different numerical approaches are being used to obtain thermal and hydrodynamic performance of porous volumetric receivers [2] and results for the temperature distribution in the receiver [3] and thermal and hydrodynamic performance [4] have been reported. Computational Fluid Dynamics (CFD) techniques combined with Monte Carlo Ray Tracing (MCRT) method based on the continuous-scale approach of the porous media is the most used strategy [2] because less computational effort is needed while good accuracy of results are obtained. Regarding internal geometry of the receiver, high porosity and pores size should be used aiming to increase the thermal efficiency and keep low pressure drop [4]. The literature shows a gap in the effect of the thickness of porous volumetric receivers on their thermal and hydrodynamic performance. One of the few examples is the work by Barreto et al. [4], where it is shown that the thickness should be selected such that the transmission losses are negligible, however, numerical simulations to support that finding was not presented yet. To fill this gap, in this work the thermal and hydrodynamic performance of two optimised internal geometries (porosity and pores size) of a volumetric receiver element made of open SiC ceramic foam are investigated for different thicknesses using an in-house detailed numerical model.

2. Receiver modelling

The receiver is modelled by solving the steady state volume averaged governing equations through the OpenFOAM [3], an open source Computational Fluid Dynamics (CFD) software. The source term of energy equation is the distribution of absorbed solar radiation in the solid matrix structure Q_{solar}, which is modelled through a Monte Carlo Ray Tracing (MCRT) method [5]. A parabolic dish is used to generate the concentrated solar radiation flux in the receiver aperture [5]. The governing equations are mass, momentum, energy equation of the fluid and solid phases and radiative transfer equation, which are described, respectively, as [3]:

$$\nabla \cdot (\rho_f \vec{U}) = 0 \tag{1}$$

$$\frac{1}{\phi}\nabla\left(\rho_f \frac{\vec{U}\cdot\vec{U}}{\phi}\right) = -\nabla p + \nabla\cdot\left(\frac{\mu_f}{\phi}\nabla\vec{U}\right) + \vec{M}_s \tag{2}$$

$$\nabla \cdot (\rho_f c_p \vec{U} T_f) = \nabla \cdot (\lambda_{fe} \nabla T_f) + h_v (T_s - T_f) \tag{3}$$

$$0 = \nabla \cdot (\lambda_{se} \nabla T_s) + h_v (T_f - T_s) - \kappa_a \big(4\sigma T_s^4 - G\big) + Q_{solar} \tag{4}$$

$$-\nabla \cdot \left(\frac{1}{3\beta}\nabla G\right) = \kappa_a \big(4\sigma T_s^4 - G\big) \tag{5}$$

where ρ_f, μ_f, c_p, $\vec{U}$ and p are the density, dynamic viscosity, specific heat capacity, superficial velocity and pressure, respectively. T_f and T_s are the fluid and solid temperature, and λ_{fe} and λ_{se} are the effective thermal conductivities of the fluid and solid, respectively. h_v is the volumetric heat transfer coefficient [6], and ϕ and d_p are the porosity and the pores size of the receiver, respectively. κ_a and β are absorption and extinction coefficients of the porous media, respectively, σ is the Stefan Boltzmann constant, G is the incident thermal irradiance and $\vec{M}_s$ stand for a momentum source due to the porous media [7].

3. Results and discussion

A cylindrical receiver element made of open-cell silicon carbide (SiC) ceramic foam with radius 2.5 cm and thickness $H = 5$ cm is considered as a reference configuration. The heat transfer fluid is considered to be air and the radiative and thermal properties of the ceramic body are: emissivity of 0.84 [8]; asymmetry factor of the scattering phase function of -0.25 [9]; and thermal conductivity of 80 W m^{-1} K^{-1} [3]. For the concentration system, a concentration factor of 500 is used and a direct normal irradiance of 800 W m^{-2} for clear sky conditions is considered. A velocity of 1.5 m s^{-1} and fluid temperature of 300 K are imposed at the receiver inlet, and a pressure of $1.013\,25 \times 10^5$ Pa is fixed at outlet. For more details of the reference configuration, see the work of Barreto et al. [4].

3.1. Optimum porosity and pores size

Regarding porosity and pores size, Barreto et al. [4] present an extensive parametric analysis for a fixed thickness of $H = 5$ cm, and two receiver element configuration with optimised internal geometry are highlighted. The geometric parameters of these receiver configurations, thermal efficiency η_{th}, bulk temperature of the fluid at receiver outlet $\overline{T}_f$ and pressure drop Δp are presented in Table 1. Figures 1 and 2 present the distribution of fluid and solid temperature in an axisymmetric cross section of these two configurations.

Table 1. Thermal and hydrodynamic performance of two receiver configurations with optimised internal geometry.

Receiver	ϕ	d_p (mm)	η_{th} (%)	$\overline{T}_f$ (K)	Δp (Pa)
A	0.85	4.5	80.67	461.73	80.64
B	0.90	3.0	80.34	460.97	100.86

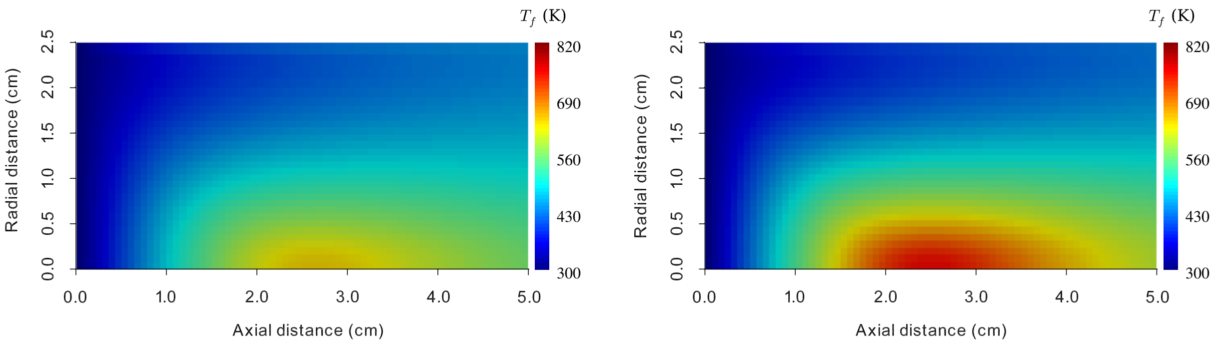

Figure 1. Temperature distribution in fluid phase (T_f) of receiver configurations (a) A and (b) B.

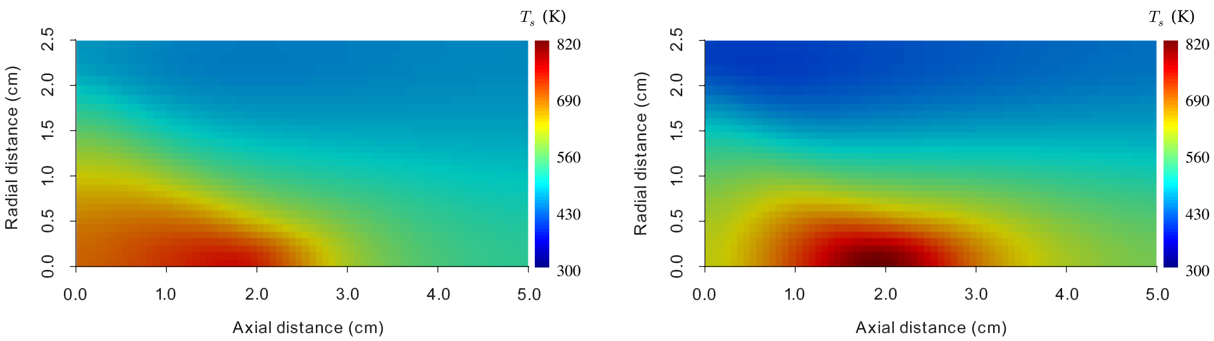

Figure 2. Temperature distribution in solid phase (T_s) of receiver configurations (a) A and (b) B.

3.2. Effect of the receiver thickness

To investigated the effect of thickness on the performance of porous volumetric receivers, simulations for receiver configurations with different thickness using the internal geometries of Table 1 are conducted. Figure 3 presents the effect of the receiver thickness on the thermal efficiency, bulk temperature at the outlet and pressure drop. Smaller receivers have lower thermal efficiency and pressure drop. The lower thermal efficiency for smaller thicnesses is mainly due to the higher transmission losses of solar radiation. Increasing the thickness of the receiver results in an increase the pressure drop, while thermal efficiency does not significantly increase after a certain thickness (thermal efficiency increase limited to approximately 81.70%), which value depends on the selected porosity and pores size.

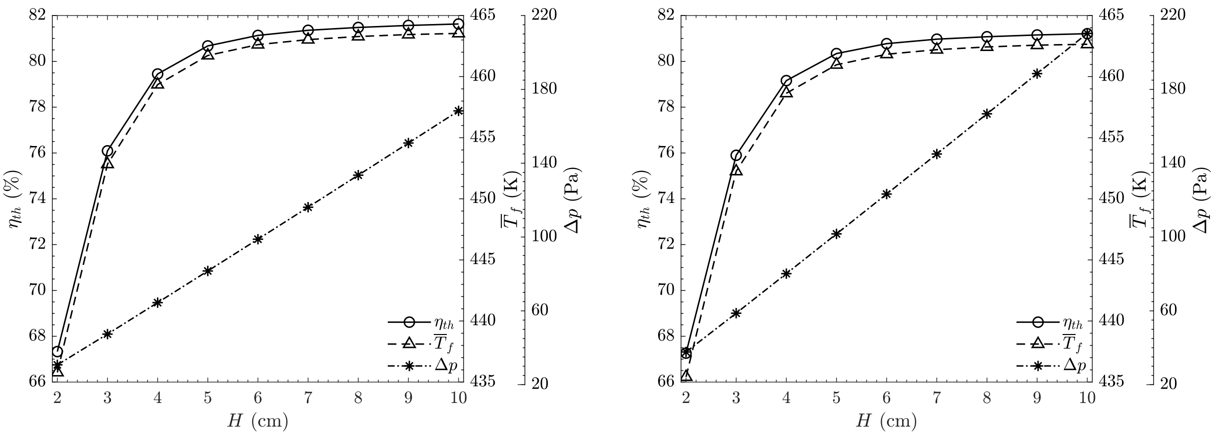

Figure 3. Thermal and hydrodynamic performance of the receiver configuration (a) A and (b) B with different thicknesses.

4. Conclusion

In this work, an in-house detailed numerical model is used to assess the effect of thickness on the thermal and hydrodynamic performance of porous volumetric solar receivers made of open-cell SiC foam. Two receiver configurations with optimised internal geometry (porosity and pores size) and adiabatic side-walls are considered for simulations. It was found that the thickness of the receiver should be chosen aimed mainly to minimise the transmission losses of solar radiation. Depending on the optimum porosity and pores size, there is a thickness from which the increase in thermal efficiency is limited to approximately 81.70% while the pressure drop always increase. The thickness should be between 5 and 7 cm for the optimium internal configurations studied aiming to increase the thermal efficiency and keep a low pressure drop.

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