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Modelling and testing of a solar-receiver system applied to high-temperature processes

M.I. Roldán [a,*], E. Zarza [a], J.L. Casas [b]

[a] CIEMAT-Plataforma Solar de Almería, Crta. de Senés, km. 4.5, E04200 Tabernas, Almería, Spain
[b] Universidad de Almería, Ctra. Sacramento s/n, E04120 La Cañada de San Urbano, Almería, Spain

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ABSTRACT

Solar volumetric-receivers have been successfully used in both electricity production and thermo-chemical applications. This paper studies the applicability of this technology to the production of process heat for high-temperature uses (573–1073 K).

As such, a volumetric-receiver system was designed, installed and tested in the Plataforma Solar de Almería's Solar Furnace (SF-60). The facility consisted of an open-volumetric-receiver module connected to a concentrated-solar-energy driven prototype, whose design was based on a previous three-dimensional CFD model.

This work focuses on the validation of the CFD model and on the experimental evaluation of the high-temperature solar prototype, taking into account the uncertainty of the experimental and simulation results. Numerical results were in appreciable agreement with the experimental data, which determined that the prototype was able to reach the high-temperature range (850 K) with a homogeneous thermal profile.

1. Introduction

Volumetric-receiver technology is an emerging option in solar thermal power plants. This receiver concept consists of a porous structure which absorbs solar radiation at different depth through its thickness. Thus, the porous material is heated by the solar radiation and a heat transfer fluid gains the energy supplied by this structure when it flows through the pores.

Atmospheric air as heat transfer fluid has advantages in terms of availability, cost and environmental impact compared to other commercial fluids [1]. Therefore, since the 1980s, different air volumetric-receiver designs were developed. Some of these designs reached air temperatures up to 1273 K, allowing their application in high-temperature processes [2]. Thus, this study intends to evaluate the applicability of using a solar air volumetric-receiver for process-heat generation at high-temperature ranges.

The integration of solar thermal power in high-temperature industrial processes has been studied by different authors [3–5] using Computational Fluid Dynamics (CFD) for the modelling of high-temperature solar devices in order to optimise prototype designs and to increase the efficiency of the high-temperature process [6,7]. Some studies have combined Monte-Carlo Ray Tracing (MCRT) and Finite Volume Method (FVM) to analyse solar porous media receivers [5–9]. Z'Graggen et al. [5] modelled a chemical reactor installed in a high-temperature solar furnace for the steam-gasification of carbonaceous materials using advanced Monte-Carlo and finite-volume methods. This model also coupled radiative, convective and conductive heat transfer to the chemical kinetics for polydisperse suspensions of reacting particles. Numerical results showed the influence of particle-size distribution on the absorption coefficient and chemical kinetics, whilst directly affecting heat and mass transfer [5]. Wang et al. coupled MCRT and FVM to study both the heat transfer in porous media receiver with multi-dish collector [6] and the thermal performance of porous media receivers which absorb concentrated solar radiation [9].

The hydrogen production from methane cracking was also a high-temperature process which was studied and analysed by CFD in order to model the behaviour of a solar chemical reactor. In this case, a numerical 2D model coupled the transport phenomena for predicting the temperature distribution with the species concentration profiles in the reactor. Simulation results determined the main areas where the reaction tended to take place [6].

* Corresponding author. Tel.: +34 950387900x839.
E-mail address: mariaisabel.roldan@psa.es (M.I. Roldán).

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Nomenclature

c_p	specific heat capacity, J/kg K
E	energy transfer, J/kg
F	external body force, N
g	gravitational acceleration, m/s^2
h	sensible enthalpy, J/kg
J	diffusion flux, kg/s m^2
k_{eff}	effective thermal conductivity, W/m K
p	static pressure, N/m^2
P	thermal power, W
Q_{EAS}	equiangle skew, dimensionless
S_h	volumetric heat source, W/m^3
S_m	mass source, kg/s m^3
t	time, s
T	temperature, K
u_τ	friction velocity, m/s
v	velocity, m/s
x	position in axis x, m
y^+	wall Y plus, dimensionless
y_P	distance from point P to the wall m

Greek symbols

α	absorption coefficient, m^{-1}
λ	thermal conductivity, W/m K
μ	viscosity, kg/m s
ρ	density, kg/m^3
τ	stress tensor, N/m^2

Subscripts

a	air
f	frame
h-e	heat exchanger
is	insulating
j	species
p	prototype
r	refractory
re	retained
w	wall

Ozalp et al. [7] evaluated different configurations of a thermochemical reactor directly irradiated by solar energy in order to produce hydrogen from natural-gas reforming. The objective of this work was to determine the influence of feed-flow behaviour on heat transfer. Global absorption and scattering coefficients were included in the computational domain to consider the radiation heat transfer from carbon particles. Furthermore, the effect of swirl on turbulence was taken into account using a specific flow model, thereby enhancing the accuracy for the swirl flows. As a result, it was determined that radiation heat transfer had a greater influence than conduction and convection, and also that the reactor geometry had a strong effect on flow behaviour [7]. In addition, other investigation [10] determined that incoming solar radiation has a significant influence on the hydrogen obtained in the methane-reforming process, where a solar volumetric-receiver was used as a thermochemical reactor.

Thus, several authors have considered volumetric solar-receivers as thermochemical reactors [10,11]. However, this technology was originally used in solar power plants to convert concentrated solar radiation into high-temperature heat so as to operate a thermal engine which produces electricity [12,13]. In this type of solar-receiver, a porous material absorbs concentrated-solar radiation on its surface, which transfers the heat to a working fluid. The behaviour of these thermal systems was analysed using numerical modelling to determine fluid mechanics and heat transfer properties [12], thermal efficiencies of different designs [14], optimum working conditions [15] and to predict the thermal behaviour of the receiver [16].

Consequently, this work presents the process-heat generation at high-temperature ranges (573–1073 K) as a new and different application of solar volumetric-receivers. As such, a volumetric-receiver system was designed, installed and tested in the Plataforma Solar de Almería's Solar Furnace (SF-60 PSA Solar Furnace). The facility consisted of an open-volumetric-receiver module connected to a concentrated-solar-energy driven prototype, whose design was obtained from a previous three-dimensional CFD model [17]. The solar prototype consisted of three layers of material (refractory, insulation and frame) and its choice of design was based on the achievement of the highest temperature range with the most homogeneous thermal profile. Therefore, the thermal behaviour of different prototype configurations was analysed by the CFD model developed. Several geometries and refractory materials with various thicknesses were proposed in order to determine the prototype design with the best geometry, the most suitable refractory material and the most appropriate material thicknesses. The CFD model solved the continuity (1), momentum (2) [18] and energy (3) [19] equations in order to define the fluid dynamic behaviour [20]:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \cdot \vec{v}) = S_m \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \cdot \vec{v}) + \nabla(\rho \cdot \vec{v} \cdot \vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \cdot \vec{g} + \vec{F} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \cdot E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \cdot \vec{J}_j + \left(\bar{\bar{\tau}}_{eff} \cdot \vec{v} \right) \right) + S_h \tag{3}$$

where ρ is the density of the fluid, t is elapsed time, $\vec{v}$ is the velocity vector with respect to the 3D coordinate system, S_m is the mass source, p is the static pressure, $\bar{\bar{\tau}}$ is the stress tensor, $\rho \cdot \vec{g}$ is the gravitational body force, $\vec{F}$ is external body forces, E is the energy transfer ($E = h - \frac{p}{\rho} + \frac{v^2}{2}$), k_{eff} is the effective conductivity which includes the turbulence thermal conductivity, h_j is the enthalpy of species j, $\vec{J_j}$ is the diffusion flux of species j, $\bar{\bar{\tau}}_{eff}$ is the viscous stress tensor and S_h is volumetric heat sources. These general equations take into account the three dimensions of the Cartesian coordinate system.

As a result of the numerical evaluation, the prototype design was chosen accordingly. This paper focuses on the model validation and the experimental evaluation of the solar prototype. Firstly, a validation methodology was developed, by considering the uncertainty of both the experimental measurements and the simulation results, to analyse the approach between experimental and simulation data, and, consequently, to determine the model predictability. Following this, the experimental evaluation of the solar prototype was developed to determine the applicability of using solar volumetric-receivers for process-heat generation at high-temperature ranges (573–1073 K).