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Experimental study of ceramic foams used as high temperature volumetric solar absorber

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ABSTRACT

Volumetric absorbers appear to be a promising technology in order to heat air above 1000 °C to feed combined-cycles (Brayton and Rankine thermodynamic cycles in cascade) for solar thermal electricity production. Thus, the choice of the absorber characteristics (material, geometrical parameters) is the key parameter to reach a maximum solar-to-thermal energy conversion efficiency. In this study, a test bench was developed and the solar-to-thermal efficiency of reticulate porous ceramics with open pores was characterized. Improvements with current state-of-the-art were made by the use of a homogenizer, ensuring spatially homogenized concentrated solar flux irradiation. Fluxmetry and calorimetry measurements were realized to evaluate the flux map incident on the tested absorber samples. A co-current position for the solar incoming power and the air flow rate was chosen for future comparisons with numerical predictions of atmospheric volumetric receivers. Several foam samples currently available in the industry were tested (Silicon Carbide, SiC) covering a wide range of porosity (72–92%) and pores per inch (5–20). A new selective material was also investigated (Zirconium Diboride, ZrB_2). Experimental results for random foams were compared to the SiC honeycomb absorber considered to be the reference volumetric receiver. In the literature, two trends were proposed to produce the best performances: (1) the use of foams with large pore diameters and high porosity and (2) the use of small pore diameters with low porosity. This study showed the second trend resulted in the best absorber efficiency. In addition, the use of selective materials was found promising for atmospheric air receiver, provided the solar absorptivity and the durability could be controlled.

1. Introduction

The competitiveness of Solar Power Tower (SPT) for electricity production may be increased by using high efficiency thermodynamic cycles (Kribus et al., 1998; Schwarzbözl et al., 2006; Romero-Alvarez and Zarza, 2007) such as Combined Cycles (CC) including high temperature gas-turbine and a steam-turbine in cascade. This corresponds to a Brayton cycle as a first stage followed by a Rankine cycle as a second stage. High temperature working fluid (e.g. gas) to power the gas turbine may be obtained either with solar energy alone or by hybridization with a combustion chamber. In the hybrid concept, the higher the working fluid temperature at the solar receiver exit, the lower the fossil fuel consumption. Temperature in the range 1000–1500 K may be obtained by absorbing media (opaque or semi-transparent) converting the concentrated solar radiation into heat, carried by a Heat Transfer Fluid (HTF). The HTF and the working fluid are the same when pressurized air flows through the solar receiver. A high temperature heat exchanger is needed if atmospheric air in used in the receiver.

Solar receivers could be classified into three groups: (1) Surface receivers (tubular, external, cavity), (2) Porous receivers (wire mesh, ceramic or metallic foams, honeycombs, ducts, packed beds), and (3) Particle receivers (falling curtain, entrained particles). At high temperature, all solar receiver efficiencies tend to decrease due to thermal emission (infrared radiation) of the materials toward the environment. For surface receivers, the wall temperature is always higher than the HTF temperature, and thus the thermal-mechanical behavior at high temperature (above 1200 K) becomes the main concern (thermomechanical stresses, oxidation and ageing).

Research on volumetric solar absorber started in the early beginning of the 80s (Olalde et al., 1980, 1985; Geneviève et al., 1980; Olalde and Peube, 1982; Flamant and Olalde, 1983; Avila-Marin, 2011). At that time, volumetric solar receivers use

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Nomenclature

Latin symbols

C	concentration ratio [–]
C_p	heat capacity [J/kg K]
I	radiative intensity [W/m^2 sr μm]
L	sample length [m]
$\dot{m}$	mass flow rate [kg/s]
N_P	number of pores crossed
Q	heat transfer rate [W]
S	surface [m^2]
T	temperature [K]

Greek symbols

α	absorptivity [–]
η	efficiency [%]
ρ	reflectivity [–]
τ	transmissivity [–]
φ	flux density [W/m^2]
ϕ	porosity [%]

Subscripts

Ag	silver
b	blackbody
c	calorimeter
f	fluid
I	index
in	inlet
ir	infrared
N	normalized
out	outlet
pix	pixel
s	solid
sol	solar
$S \rightarrow T$	solar-to-thermal
w	water
λ	wavelength

Abbreviations

CC	Combined Cycles
DNI	Direct Normal Irradiation
HTF	Heat Transfer Fluid
IR	Infrared
PPI	Pores Per Inch
RPC	Reticulate Porous Ceramic
SPT	Solar Power Tower

mainly silicon carbide SiC materials (particles and honeycombs) at atmospheric air pressure and small scale (under 10 kW). Co-current and counter-flow for solar radiation and air flow were studied (Olalde et al., 1980, 1985; Olalde and Peube, 1982). Concerning the use of particles, packed bed and fluidized bed were compared (Flamant and Olalde, 1983) using silicon carbide SiC particles and zirconia ZrO_2 particles.

During the 90s, investigations on volumetric solar absorbers began to separate in two main categories: theoretical studies on the one hand, involving modelling, numerical simulations, parametric studies (Carotenuto et al., 1991; Pitz-Paal et al., 1991; Kribus et al., 1996) and experimental studies on the other hand. Similarly with 80s studies, silicon carbide was chosen as foam and honeycomb structures (Böhmer and Chaza, 1991; Carotenuto et al., 1993), but some new materials were investigated as well: alumina foams Al_2O_3 (Chavez and Chaza, 1991; Karni et al., 1997; Kribus et al., 1998), metallic foams and wire mesh structures as Ni-alloys and Inconel (Pitz-Paal et al., 1997). One may also remark that the power of the tests bed increased, reaching pilot scale (200 kW_{th} for Chavez and Chaza, 1991) as well as semi-industrial scale (2.70 MW_{th} for the solar tower involved in Böhmer and Chaza, 1991; Carotenuto et al., 1993). The use of pressurized air instead of atmospheric air have also been investigated (Karni et al., 1997; Kribus et al., 1998., 1999), but highlighting some technical problems due the use of high pressure high temperature window (Pritzkow, 1991). The concept of a multi-stage receiver was also studied (Kribus et al., 1999), consisting of two stages in series: the first one made of a tubular cavity and the second one using RPC materials.

After years 2000, the number of studies and projects increased, and due to improvements in numerical calculation and computing power, the most recent works on the subject since 2000 focused on numerical analysis, modelling and optimization (Becker et al., 2006; Hischier et al., 2009; Bai, 2010; Smirnova et al., 2010; Wu et al., 2011a, 2011b; Xu et al., 2011; Cui et al., 2012; Sano et al., 2012; Cheng et al., 2013a, 2013b; Fend et al., 2013; Gómez et al., 2013; Sano and Iwase, 2013; Wang et al., 2013a, 2013b; Wu and Wang, 2013; Gomez-Garcia et al., 2014, 2015; Kribus et al., 2014a, 2014b; Mey et al., 2014; Ordoñez et al., 2014; Roldan et al., 2014; Chen et al., 2015), with still some experimental studies (Fend et al., 2004a, 2004b; Heller et al., 2006; Schwarzbözl et al., 2006; Palero et al., 2008; Albanakis et al., 2009; Michailidis et al., 2013; Avila-Marin et al., 2014; Sharma et al., 2014; Roldan et al., 2015). The number of materials investigated widely increased, including different metals and alloys (nickel, Ni-alloys as Nichrome, copper, aluminum, Inconel) in foam and wire mesh structures (Albanakis et al., 2009; Avila-Marin et al., 2014). Instead of using solar furnace, some work used a “solar simulator” (Avila-Marin et al., 2014). The study of multi-stage receiver was also developed (Heller et al., 2006), adding one intermediate stage and integrating a small gas turbine.

During these researches and development phases, some innovations were made regarding the design of volumetric solar absorbers able to reach higher solar-to-thermal energy efficiencies and higher temperatures.

Two ways of using spectral selectivity have experimentally been investigated: first by Menigault et al. (1991) and Variot et al. (1994), with a two-slab selective receiver using silica SiO_2 and SiC particles and secondly by Pitz-Paal et al. (1991), with quartz and SiC honeycombs. The radiative behavior of these materials (SiO_2 and quartz) makes them transparent to solar radiation, while highly absorbing in infrared spectrum, blocking reemitted infrared radiation by the SiC structure inside the receiver, decreasing the heat losses due to thermal radiation. With the resulting greenhouse effect, Menigault et al. (1991) first demonstrated the presence of a volumetric effect in the absorber (i.e., the outlet air temperature is higher than the solid inlet temperature). Gradual geometrical properties was also studied aiming at two objectives: the first one was to increase the temperature inside the volumetric absorber using multi-layer materials with various properties (as in Fend et al. (2004a)), and the second one using radial gradient of porosity under non-homogeneous flux (as in Avila-Marin et al. (2014)). Flow stability was also studied in honeycomb structures over the years, investigating the operating conditions leading to