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Experimental results of gradual porosity wire mesh absorber for volumetric receivers

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Abstract

Concentrated Solar Power (CSP) market is focused in the cost reduction by means of increasing efficiencies and reducing the investment, installation and, operation and maintenance costs. In Concentrated Solar Power with Central Receiver (CR) technologies, one option for increasing efficiency is to raise the temperature of the working fluid. The CSP-CR technology working with volumetric air receiver shows a high potential to improve efficiencies by allowing higher operating temperatures (above the limit of commercial power tower plants).
However, most of the different volumetric receivers tested during the last three decades did not match the predicted nominal conditions, working at lower efficiencies than expected. Other challenges still remain unsolved, like absorber durability, and the specific cost.
In order to identify high-efficient configurations and geometries for the absorbers used as volumetric receivers, CIEMAT-PSA (funded by SOLGEMAC project) has developed a lab-scale test bed used for the evaluation of open volumetric receivers.
The main goal of the installation is to identify different configurations and geometries that improve the thermal efficiency of the reference open-loop volumetric receivers: Phoebus-TSA for metallic materials and SOLAIR for ceramic ones.
The initial tests of the installation are focused on characterized the TSA and the SOLAIR absorbers. Then, a comparison with the newer designs will be made in order to improve the reference absorbers.
First results with the SOLAIR absorber made of recrystallized SiC with an open porosity of 49.5 %, for a mean air outlet temperature varying from 266-to-623 ºC, moves from 89-to-56% thermal efficiency.
For the newer designs, CIEMAT-PSA has AISI 310 commercial wire meshes with different characteristics. The wire ranges from 0.13-to-1.00 mm, and the mesh size varies from 0.20-to-4.00 mm. With different combinations of the meshes, several prototypes will be analyzed.

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Keywords: Absorber; ceramic materials; metallic materials; volumetric receivers; central receiver system.

1. Introduction

The increasing problems of CO_2 emissions and the fossil fuel costs have strengthened interest in alternative, nonpetroleum-based sources of energy. Among the variety of technologies of Solar Thermal Power Plants (STPP), Central Receiver systems with open volumetric absorber appear as a promising scheme that could increase receiver and BOP efficiencies both reducing radiative thermal losses, and raising the temperature of the Heat Transfer Fluid (HTF).

Volumetric receiver development dates back to 1983 with first prototype [1]. The highly porous structure of volumetric receivers may be metal or ceramic. Since ceramics are the most appropriate materials for achieving the highest air temperatures, this is the most suitable option when temperatures above 800ºC are necessary. On the other hand, metallic receivers allow higher heat transfer between air and the structure and quicker response. For CR systems with open volumetric absorber there are two reference receivers: TSA for metallic materials and SOLAIR for ceramics [2].

The TSA absorber tested in PSA was made up of Inconel 601 coiled knit-wire knitted packs. The main result of the tests carried out in 1993 was the ability to achieve the design absorber efficiency of 85% at 700ºC receiver air outlet temperature at an average flux density of 300 kW/m^2 and an air return ratio of 60%. The main conclusions from the tests of the 2.5 MW_{th} volumetric air receiver project were that the system control was able to maintain air outlet temperatures constant, the modular design would facilitate future plant scale-up, the ability to match the air flow distribution of the absorber with the incident flux distribution and the flexibility of the process [2].

The SOLAIR absorber tested in PSA was made of re-SiC with a porosity of 50%. The receiver was a modular absorber assembled from 270 ceramic cups made of SiSiC. The results showed that the efficiencies varied in the range of 70-to-75% at 750ºC receiver air outlet temperature for mean solar fluxes in the range of 370-to-520 kW/m^2 and an air return ratio of 50% [2]. In June 2006, it was decided to build a central receiver plant with volumetric receiver (SOLAIR technology) and thermal storage in Jülich, Germany. The aim of the project was to demonstrate this technology in a complete pre-commercial power plant for the first time [3].

In spite of this nice project results, most of the different volumetric receivers tested during the last three decades did not match the predicted nominal conditions, working at lower efficiencies than expected. In order to identify high-efficient configurations and geometries for the absorbers used as volumetric receivers, CIEMAT-PSA (funded by SOLGEMAC project) has developed a lab-scale test bed used for the evaluation of open volumetric receivers.

The main target of the facility is to identify different configurations and geometries that improve the thermal efficiency of the reference volumetric absorbers: TSA and SOLAIR. For that purpose, CIEMAT-PSA is developing with commercial AISI 310 different volumetric absorbers structures with gradual porosity.

Gradual porosity volumetric absorber is a promising innovation that addresses to solve the main thermal problems of this technology. The basic objectives of gradual porosity is to reduce the front surface of the absorber, which means lower radiative losses, and on the other hand, promote the basic principle of a volumetric which is the absorption of the radiation in the depth of the structure.

Nomenclature

CSP	Concentrated Solar Power (CSP)
CR	Central Receiver
STPP	Solar Thermal Power Plants
HTF	Heat Transfer Fluid
BOP	Block Of Power
P	Power (W)

$\bar{\phi}$	Incident solar simulator flux (kW/m^2)
m	Mass flow rate (l/h)
ρ	Density (kg/m^3)
c_p	Specific heat (J/kg/K)
T	Temperature (K)
I_0	Incidence radiance
I	Transmitted radiance
τ	Path length
re	Recrystallized

Subscripts

w	water
in	inlet
out	outlet
HE	heat exchanger
x, y, z	cartesian coordinates
rec	receiver
abs	absorber
th	thermal

2. Experimental

2.1. Facility description

CIEMAT-PSA has developed a new facility, Fig. 1, for the thermal evaluation of open volumetric receivers. It is composed by four sub-systems:

- Fig. 1A 4 kW solar simulator made up of a xenon lamp and a parabolic concentrator that can reach fluxes of up to 1900 kW/m^2 which corresponds to stagnation temperatures above 2400K.
- A receiver sub-system where the different volumetric absorbers are placed. It is equipped with 23 K-type thermocouples, 1 S-type thermocouple, 1 T-type thermocouple, 2 PT100 surface sensors and an infrared camera.
- An helicoidal air-water heat exchanger sub-system equipped with 4 PT100 sensors, 2 PT100 surface sensors, 1 T-type thermocouple, a water mass flow-rate measurement, and a pump.
- An extraction sub-system with 1 PT100 sensor, an air mass flow-rate measurement, and a blower.

The blower forces the ambient air to flow through the volumetric absorber while heating up. Then the air is the energy carrier fluid which circulates counter current in a water heat exchanger in order to reduce the air temperature to protect the blower and to get an indirect measurement of the receiver efficiency. Moreover, as a security measure to protect the blower, there is an auxiliary ambient air inlet just at the blower entrance, regulated with a bypass valve, so the temperature of the air passing through is below the limit for the blower.

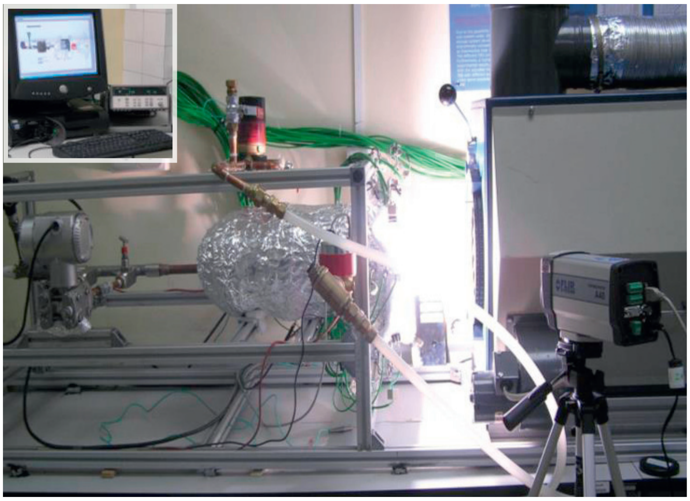

Fig. 1. Test facility for the thermal evaluation of open volumetric receivers with a 4 kW xenon arc lamp

2.2. Absorber materials

Volumetric receivers are exposed to concentrated solar radiation, high temperature, daily temperature cycles and transients, oxygen, etc.. So, the construction materials requirements are:

- High solar absorption (black),
- High heat transfer,
- Low thermal gradients and thermal stresses and,
- High temperature resistance to any degradation.

Taking into account the temperature operation and materials cost, three candidates has been tested. SiC (SOLAIR absorber) for temperatures higher than 1000 ºC, with thermal conductivity of 78 W/m/K and thermal expansion coefficient 4.0 µm/m/°C. For temperatures up to 1000 ºC, one nickel based alloy and one stainless steel, both with high chromium content has been tested. Table 1 shows their composition and properties. Alloy 601 (TSA absorber) was tested due to its good properties for high temperature oxidation and its ability to form black oxides, increasing the absorptance. Alloy 310, with lower Cr content, has better mechanical properties at high temperature than 601, in order to withstand the thermal stress due to operation.

Table 1. Composition and main thermal properties of selected alloys

Alloy	Ni	Cr	Fe	Other	Thermal conductivity, W/(m*C)	Thermal expansion, µm/m/°C
601	61	23	15	Al 1.4	26.1	17.8
310	20	20	59	Si 1.5	14.2	19.1

For the newer designs, CIEMAT-PSA has AISI 310 commercial wire meshes with different characteristics. The wire ranges from 0.13-to-1.00 mm, and the mesh size varies from 0.20-to-4.00 mm. The selected meshes characteristics are shown in Table 2.

The thickness of the newer designs was optimized experimentally by means of the extinction coefficient that varies with the mesh porosity. The extinction coefficient of different mediums, which can be used as a tool to approximate radiation analysis in semitransparent mediums, follows the Bouger’s law.

$$I = I_0 \cdot e^{(-\tau)} \tag{1}$$

Table 2. Commercial AISI 310 wire mesh characteristics

Material	AISI 310		
Wire diameter, mm	0.63	0.50	0.70
Mesh size, mm	1.00	1.40	2.50
Porosity, %	38	54	61

Table 3 presents the main characteristics of the gradual porosity absorbers made of 310 alloy.

Table 3. Gradual porosity absorbers characteristics constructed with 310 alloys

Absorber name	Nº mesh 61%	Nº mesh 54%	Nº mesh 38%	Thickness, mm
61-54	2	8	-	11.0
61-38	2	-	5	9.5
54-38	-	2	5	9.0

Test were carried out at different incident concentrated radiation and air mass flow rate, depending on the absorber material. Firstly, as the re-SiC absorber, used for the SOLAIR receiver, is the material recommended for temperatures above 800 ºC [2], even exceeding 1000 ºC, the experimentation for this absorber was realized in the focal plane of the solar simulator, with peak flux of up to 1936 kW/m^2 and average flux of 300 kW/m^2. In contrast with the SiC, metallic alloys working temperature should not exceed in any case 1000 ºC, and the recommended temperature should be, depending on the alloy composition, around 800 ºC. Due to this recommendation, the alloys was tested out of the focal plane to reduce very high peak fluxes. The maximum peak flux, for metallic alloys, varies from 1300-to-800 kW/m^2, with average fluxes from 260-to-220 kW/m^2. The same solar fluxes was used for 601 alloy and 310 alloy.

2.3. Thermal evaluation

The measurement of the incident solar power radiation at different planes are measured by a calibrated water-cooled calorimeter and contrasted with a CCD camera.

$$\bar{\phi}_{incident,\ z} = \int_{-y}^{y} \int_{-x}^{x} \phi_{incident,\ z}\ (x,y) \cdot dx \cdot dy \tag{2}$$

At a first approximation, for the thermal evaluation of the receiver it is assumed that the power gained by the air is transmitted to the water cooling circuit (in steady state conditions).

$$P_{air} = P_w = \dot{m} \cdot \int_{T_{w,out,HE}}^{T_{w,in,HE}} \rho \cdot c_p \cdot dT \tag{3}$$

The receiver thermal efficiency refers to the transference process from the power transmitted to the HTF at the receiver outlet to the concentrated solar energy incident on the absorber aperture.

$$\eta_{rec\_th} = \frac{P_{air}}{\bar{\phi}_{incident,z} \cdot A_{abs}} \tag{4}$$

This efficiency is a function which depends mainly on the absorber technological characteristics but also on the experimental conditions (orientation, distance to the focal plane, etc.) and on the operational conditions (output temperature regimen, input power flux, etc.). Thus, in order to estimate the efficiency function the experiments should cover different operational scenarios (incident solar flux, outlet temperature levels, etc.).

3. Results and discussion

The results of the re-SiC absorber are presented in Fig. 2.

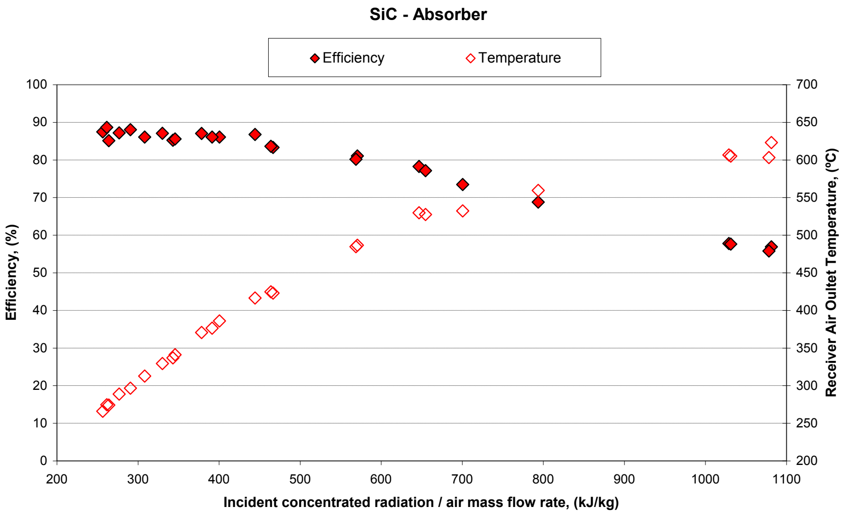

Fig. 2. re-SiC absorber efficiency and receiver air outlet temperature for different incident concentrated radiation/air mass flow rate ratios

The results of the re-SiC absorber shows that for a receiver air outlet temperature of 250-650ºC, the system reaches efficiencies of 89-60 % with a ratio of the incident concentrated radiation to the air mass flow rate of 250-1100 kJ/kg. The low thermal efficiency (~60%) at high temperatures (630ºC) is mainly explained by the radiative losses.

Fig. 3 depicts the results of the 601 alloy absorber.

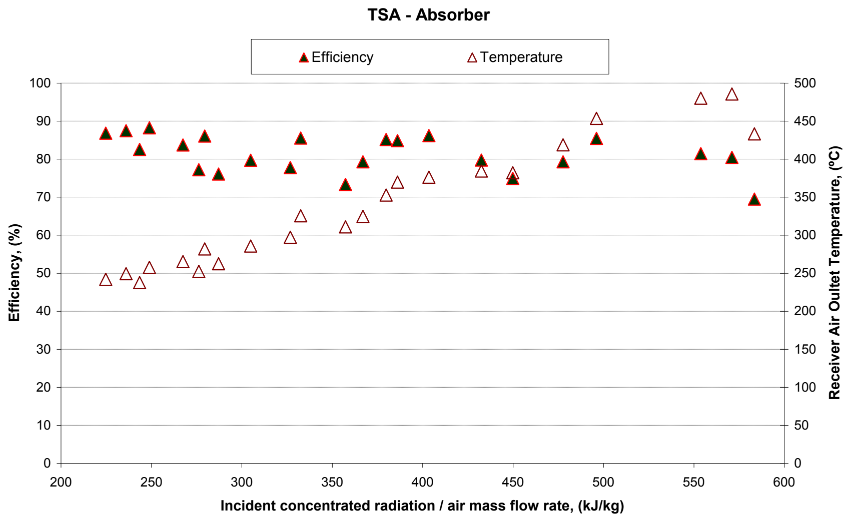

Fig. 3. 601 alloy absorber efficiency and receiver air outlet temperature for different incident concentrated radiation/air mass flow rate ratios

The test with alloy 601, depicts that for a receiver air outlet temperature of 260-500 ºC, the system reaches efficiencies of 89-70 % with a ratio of the incident concentrated radiation to the air mass flow rate of 250-600 kJ/kg. Similar results to that obtained with SiC.

Fig. 4 shows the main results for the three alloy AISI 310 gradual porosity absorbers tested. Fig. 5 presents the 54-38% absorber after tests.

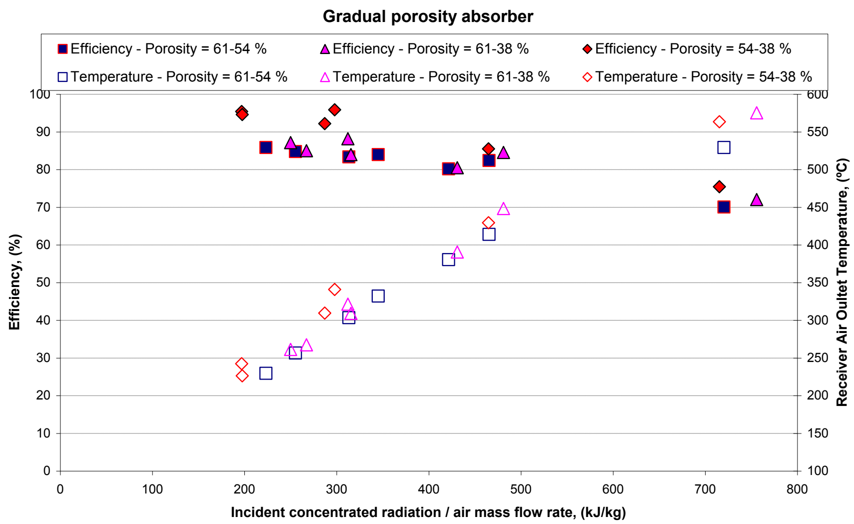

Fig. 4. Gradual porosity absorbers efficiency and receiver air outlet temperature for different incident concentrated radiation/air mass flow rate ratios

The main results for the three gradual porosity absorbers are:

- Absorber 61-54: for a receiver air outlet temperature of 230-530 ºC, the system reaches efficiencies of 86-70 % with a ratio of the incident concentrated radiation to the air mass flow rate of 230-720 kJ/kg,
- Absorber 61-38: for a receiver air outlet temperature of 320-580 ºC, the system reaches efficiencies of 88-72 % with a ratio of the incident concentrated radiation to the air mass flow rate of 310-760 kJ/kg,
- Absorber 54-38: for a receiver air outlet temperature of 340-560 ºC, the system reaches efficiencies of 96-75 % with a ratio of the incident concentrated radiation to the air mass flow rate of 300-720 kJ/kg.

Fig. 5. Gradual porosity 54-38% 310 alloy after test

Table 4 presents a summary with the main results of the 5 absorbers analyzed for similar working conditions. For low values of the incident radiation to air mass flow rate ratio, three of the absorbers – SiC, 601 alloy and 61-38% 310 alloy – present similar results (87-88%), while the 61-54% 310 alloy presents worse thermal efficiency (85%) and the 54-38% 310 alloy presents better performance (92%). On the other hand, for high values of the incident radiation to air mass flow rate ratio, which involves higher air outlet temperature, the 61-54% 310 alloy and the 61-38% 310 alloy present similar thermal results (70-72%), whilst the 54-38% 310 alloy is the only absorber that improves the thermal behavior of SiC, with an efficiency of 75.4% compared to the 73.5% of SiC.

When comparing only the metallic absorbers, for low ratio values, the same aforementioned discussion is observed, while for medium to high ratio values, all the gradual porosity absorbers present better thermal behavior than 601 alloy used in TSA receiver.

Although it is difficult to infer a trend from three gradual porosity absorbers, the poorer thermal performance of the 61-54% 310 alloy and 61-38% 310 alloy respects to the 54-38% 310 alloy could be influenced by the wire diameter. Despite the first layers of the 61-54% and 61-38% present lower material content exposed to the ambient than the 54-38% 310 alloy.

Table 4. Summary of the 5 absorbers analyzed for similar working conditions

Material	SiC			601 alloy			61-54 % 310 alloy			61-38 % 310 alloy			54-38 % 310 alloy		
Incident radiation / air flow, kJ/kg	260	440	700	250	430	580	260	420	720	250	430	760	290	470	720
Air outlet temperature, ºC	270	420	530	260	380	430	260	380	530	260	390	580	310	430	560
Thermal efficiency, %	87.5	86.8	73.5	88.2	79.8	69.5	84.8	80.2	70.1	87.1	80.5	72.0	92.2	85.5	75.4

Further experimentation is under performance to confirm the presented results and to analyze other possible geometries and configurations. In the same way, an analysis of the material behaviour during this test and long-time tests are being carried out to achieve an optimized gradual porosity absorber to be used in future plants.

4. Conclusions

This paper describes a new facility developed by CIEMAT-PSA with the aim of studying new configurations and geometries that improve the state of the art on metallic absorbers for its application in CR.

Moreover, a thermal characterization of the reference volumetric receivers, SOLAIR for ceramic absorbers and TSA for metallic absorbers, in this new facility is presented. The main results of the SOLAIR receiver show receiver air outlet temperature of 250-650ºC which corresponds to a system efficiency of 89-60%. For the TSA receiver the receiver air outlet temperature moves from 260-500 ºC with thermal efficiencies of 89-70%.

Finally, the paper presents the first results for three volumetric absorbers with gradual porosity: 61-54%, 61-38% and 54-38%. The outcomes show that the volumetric absorber with gradual porosity 54-38% has better performance than the other four absorbers.

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