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Direct Thermal Comparison of New Generation SiC Solar Absorbers

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Abstract. A new generation of volumetric absorbers has been developed to improve both the mechanical robustness of SiC ceramic structures and the thermal behaviour of the new geometric designs. Within the NEXTOWER project, two new absorber designs have been developed for these purposes, one developed to improve mechanical performance and durability, and the other aimed at improving the thermal performance of the absorbers through a new gradual porosity design. Both designs have been tested, alongside of current state-of-the-art ceramic absorbers, under real concentrated solar radiation in the SolAir3000 receiver of the Plataforma Solar de Almería. The results show that the gradual porosity design is a promising way to significantly improve the thermal efficiency of volumetric SiC absorbers. At the same time, the new manufacturing processes show a significant improvement in the mechanical strength and durability of the new generation designs.

Keywords: Central Receiver Systems, Volumetric Absorbers, Gradual Porosity, Thermal Performance, Open Volumetric Receiver

1. Introduction

Porous structures are widely used for different industrial applications such as thermal insulation, heat exchangers, industrial burners, thermal energy storage and volumetric receivers due to their interesting properties. The potential application of porous structures in solar thermal power tower plants promises, firstly, to partially solve the high thermal losses and inefficient transmission of tubular receivers, and secondly to address some of the concerns related to concentrated solar power such as electricity cost and overall plant efficiency. As a result, open volumetric receiver (OVR) technology is a candidate to replace tubular technology given its advantages and ability to operate at higher incident solar flux profiles [1].

OVR technology has been developed in various research and development projects since the 1990s. The key element of the technology is the volumetric absorber, which absorbs concentrated solar energy throughout its volume to transform it into thermal energy. The main requirements of the volumetric absorber are a high porosity, large specific surface area and high thermal conductivity to effectively transfer heat to the heat transfer fluid. Ceramic materials are the most suitable candidates to operate at temperatures above 800ºC [2].

Among ceramic materials, porous silicon carbide (SiC) holds promise for use in the next generation of OVRs, due to its outstanding mechanical, thermal, and chemical robustness, which are required to operate without failure under extreme thermal cycling at a minimum temperature of 800°C and to provide over 25 years of operation. Improving the efficiency of OVRs by addressing thermal cycling and thermal shock failures is a key driver of the European NEXTOWER research project (www.h2020-nextower.eu).

Section 2 describes the characteristics of the new SiC absorbers developed and the experimental setup to directly compare their thermal performance with the state-of-the-art technology. Section 3 deals with the experimental results of the test campaign and section 4 summarizes the conclusions of the work carried out.

2. Absorber development and experimental setup

Two different types of volumetric SiC absorbers have been developed (Figure 1) by LiqTech Ceramics A/S (left) and ENGICER S.A. (right).

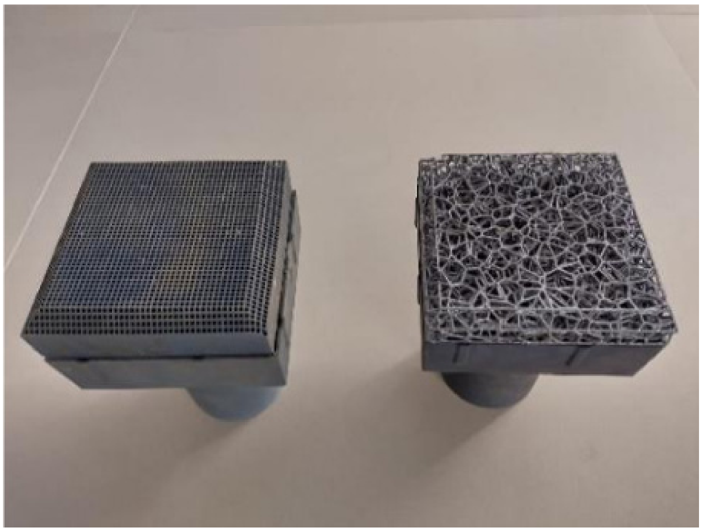

***Figure 1**. Samples of the new generation of volumetric absorbers developed into the NEXTOWER project*

The first set of absorbers were manufactured by LiqTech Ceramics A/S according to the channel design described in the literature [3]. These new absorbers were manufactured with the aim of improving the mechanical properties and durability of the absorbers without compromising their thermal performance [2]. A set of 75 125x125 mm aperture volumetric absorbers were manufactured by extrusion and partially sintered by LiqTech Ceramics A/S (Ballerup, Denmark). Two different batches of α-SiC powders were combined, with a particle size between 20 and 35 μm for the coarse batch and between 0.4 and 0.8 μm for the fine batch; this bimodal granulometry of the SiC powders is necessary in order to achieve the required recrystallization during sintering. The powders were mixed with a plasticizer, such as polyvinyl alcohol (PVA), to give the required plasticity to the mass or paste [4]; a binder; a dispersant; and a mixture of water and ethanol as the solvent. The extrusion slurry had a very high solid content, between 70 % and 80 % wt. solids. This slurry was stirred and extruded to the desired shape at a pressure of no more than 30 bar, and the final shape was achieved by cutting after drying. The dried slabs were fired in an argon atmosphere, at temperatures between 2100 and 2300 °C for 1.5 h, in a graphite furnace, where the main sintering mechanisms were evaporation–condensation at the surface of the fine powders and diffusion at the contacts between the coarse particles [4]. In order to remove any residual carbon that might remain in the pores, a surface oxidation step was carried out at a temperature of 1100 °C, for 1 h, in an air furnace.

The second set of samples (75 units), manufactured by ENGICER S.A., followed an innovative 3D design process based on Voronoy structures, which offers the possibility of introducing porosity gradients within the designed structures [5]. In this process, the designed structures are printed using polymer additive manufacturing, and these printed polymeric models serve as template structures for the ceramic shaping process [6], giving the final prototype the desired morphology. The shaping of the ceramic part is done by a replication process known as the Schwarzwalder method, which consists of coating a sacrificial polymeric template with a SiC-based ceramic slurry. The coated template structure, also called the green body, is then dried and pyrolyzed. A slow heating ramp cycle up to 1000 °C in a flowing nitrogen atmosphere is used to carefully pyrolyze the additives and the polymeric template without creating cracks from thermal expansion or volume changes from degradation reactions. All organic additives are pyrolyzed, leaving only amorphous carbon in the material matrix. At the end of the debinding cycle, a C/SiC preform (the brown body) is obtained. Finally, the brown body is processed by reactive melt infiltration with silicon at 1500 °C in a vacuum furnace. The purpose of the process is to react carbon with silicon to form silicon carbide and to fill the remaining porosity with free (unreacted) silicon to obtain a fully dense SiSiC microstructure. The final manufacturing step is an oxidation cycle carried out in air up to 1500 °C. The purpose of this final cycle is to oxidize the surface of the lattice, thereby reducing the reflected radiation.

Both sets of samples have been installed in the SolAir 3000 volumetric receiver installed in the CESA I tower at the Plataforma Solar de Almería (PSA), as is shown in Figure 2. Two matrices of 9 rows by 7 columns (63 cups in total) have been installed in the bottom half of the receiver.

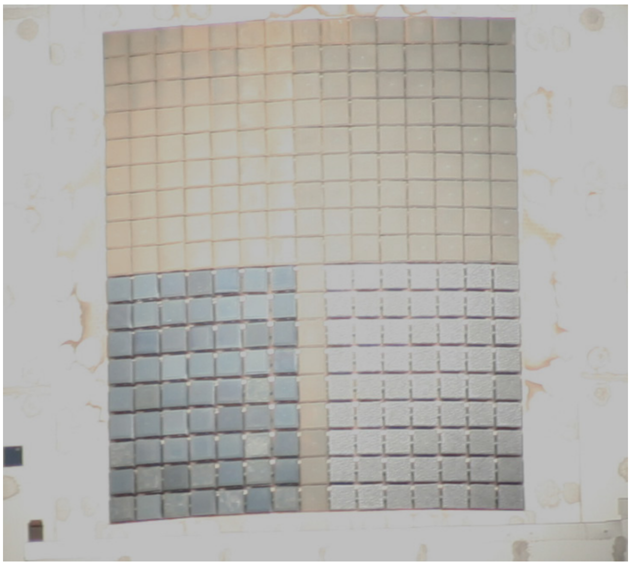

Figure 2. *Final testing configuration of SolAir 3000 receiver including state-of-the-art absorber modules (upper half) and new developed absorbers (bottom half)*

As both sets of new absorbers modules are installed together with the state of the art absorbers developed in the SolAir project [3], a direct thermal performance comparison between them can be directly performed under the following assumptions/conditions:

- Incident power is measured for each individual module using a calibrated lambertian target [7].
- The air oulet temperature in each individual absorber is measured with a thermocouple at the module outlet.

With these assumptions, the steady-state efficiency is defined by Equation 1:

$$\eta = 1 - \frac{P_{losses}}{P_i} \tag{1}$$

P_i is the radiant power incident on the absorber and P_{losses} are the thermal losses at the working temperature. Under the supposition that conduction and convection losses are negligible at high temperature compared with radiation losses, thermal losses can be expressed as (equation 2):

$$P_{losses} = \sigma e A (T_{abs} - T_{amb})^4 \tag{2}$$

Where σ is the Stefan-Boltzman constant, *e* is the emittance of the absorber, *A* is the surface of the absorber, and T_{abs} and T_{amb} are the absorbers and ambient temperatures respectively. The absorber temperatures have been estimated to be 100 °C higher than the outlet air temperature at these temperature ranges [8].

3. Experimental results and discussion

Samples of the new absorber designs were tested at temperatures up to 900 °C for almost 80 hours (Figure 3). And, as has been mentioned above, the placement of the absorbers on the receiver, the measurement of air temperature in individual modules and the incident flux distribution were chosen because they allow direct comparison between different module designs.

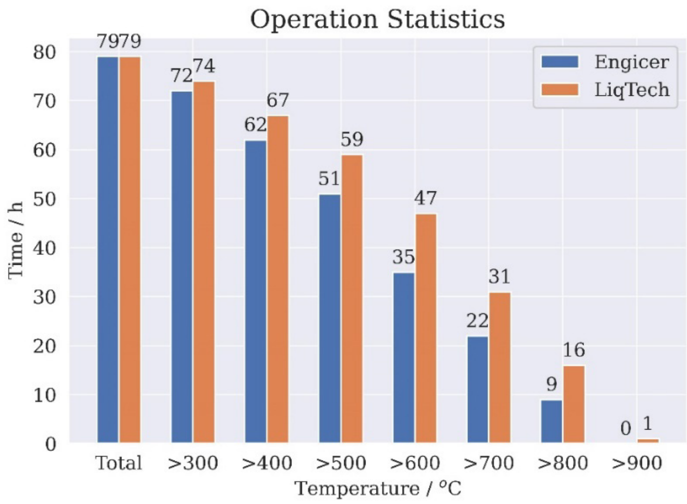

Figure 3. *Operation statistics of new absorber cups installed on the Solair3000 receiver*.

Figure 4 below shows the temperature statistics for the three module designs, the state-of-the-art SolAir, and the two new designs LiqTech and ENGICER, from one of the test days. As can be seen from the graphs, the temperatures between the SolAir state-of-the-art cups and LiqTech new design are comparable, while the temperatures reached by the ENGICER absorbers are slightly lower than the other two. This is due to the greater porosity of the latter design which allow greater air flow through the absorbers, cooling them better. The violin graphs show, in addition to the probability density of temperatures during the test, the median and the 0.05 and 0.95 percentiles. Labels are referred to the temperature signal measured in the individual absorbers, and have correspondence with the positions indicated on figure 5.

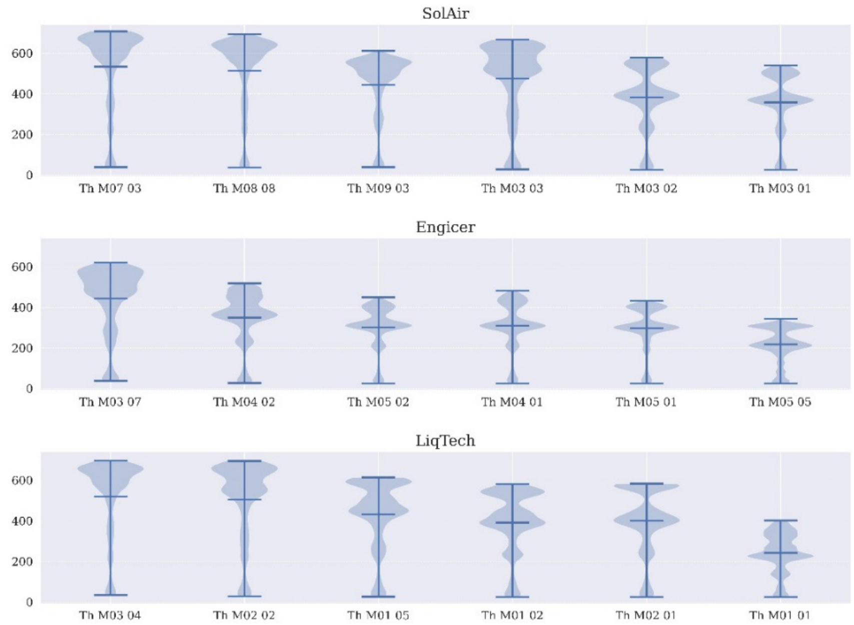

Figure 4. *Probability density graphs of the test temperatures (in °C) for the three different absorber designs tested (July, 26th).*

As explained in section 2, the thermal performance of the absorbers can be calculated directly by measuring the individual module temperatures and the incident power in the modules. Figure 5 shows the individual incident power in each one of the LiqTech and ENGICER modules for one of the test days. The flux distribution on the receiver surface shows good symmetry, given that both flux profiles incident in each one of the absorber types are almost the same, and both types of the new absorbers received equivalent incident radiation (slightly higher for ENGICER absorbers than for LiqTech absorbers).

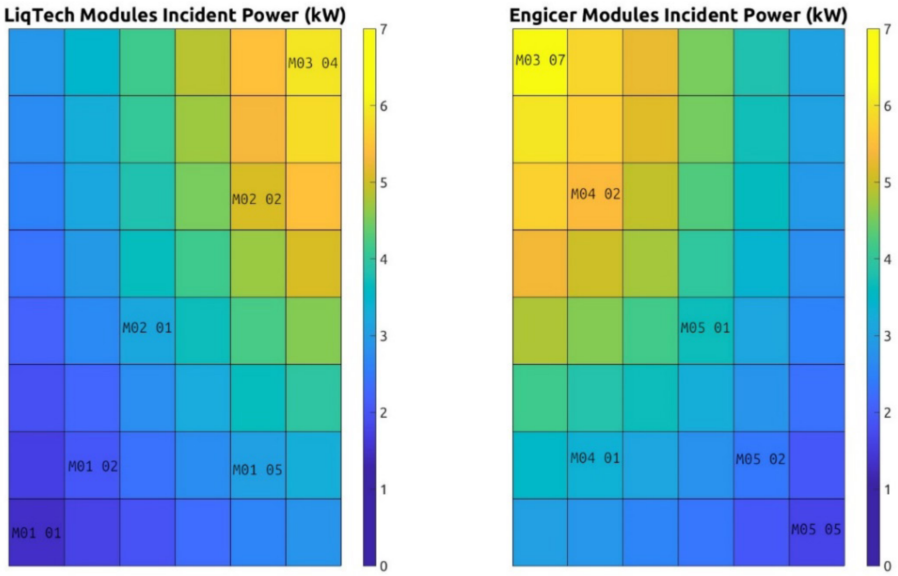

Figure 5. *Incident power in LiqTech (left) and ENGICER (right) modules for one of the test days: July, 26th at 13:25:21 local hour.*

Table 1 below is a summary of the incident power and temperatures for the different absorbers for the July, 26th test at 13:25:25 local time.

Table 1. *Incident power and temperatures of the absorber modules*

LiqTech Absorbers			**Engicer Absorbers**		
	Incident Power (kW)	**Temperature (°C)**		**Incident Power (kW)**	**Temperature (°C)**
Th M03 04	6.2 ± 0.3	652 ± 7	**Th M03 07**	6.3 ± 0.3	615 ± 6
Th M02 02	5.1 ± 0.3	575 ± 6	**Th M04 02**	4.9 ± 0.2	501 ± 5
Th M01 05	3.2 ± 0.2	385 ± 4	**Th M05 02**	3.1 ± 0.2	350 ± 4
Th M01 02	2.06 ± 0.10	356 ± 4	**Th M05 01**	1.95 ± 0.10	285 ± 3
Th M02 01	3.1 ± 0.2	426 ± 4	**Th M04 01**	3.1 ± 2	410 ± 4
Th M01 01	1.26 ± 0.06	206 ± 2	**Th M05 05**	1.07 ± 0.05	232 ± 2

With the data included on Table 1, it is possible to calculate the absorber module efficiencies following equations 1 and 2 included above, and these efficiencies can be compared between modules that are symmetrically located on the receiver. On this way, the mean value of the comparative efficiencies between the SolAir state-of-the-art and LiqTech modules and between Liqtech and ENGICER absorbers are included below.

$$\frac{\eta_{SolAir}}{\eta_{LiqTech}} = 0.98 \pm 0.09 \tag{3}$$

$$\frac{\eta_{LiqTech}}{\eta_{ENGICER}} = 0.94 \pm 0.12 \tag{4}$$

These results show that the LiqTech absorbers achieve thermal efficiencies comparable to the state-of-the-art absorbers. As can be seen in Figure 2, LiqTech absorbers are darker than the SolAir absorbers and the differences in thermal efficiency can be attributed to the improved absortance of the LiqTech modules.

On the other hand, the new gradual porosity ENGICER absorber design improves (6%) the thermal performance. Further evaluation needs to be done, but it seems that as the solar radiation goes deeper into the absorber modules, it favours higher maximum temperatures than those reached on the absorber front surface [5].

4. Conclusions

During the NEXTOWER project, a new generation of volumetric SiC absorbers was designed with the aim of improving their durability and mechanical robustness on the one hand, and their thermal behavior and therefore their efficiency on the other.

These new absorber designs were compared with the absorbers developed in the SolAir project, which in this study represent the state-of-the-art in volumetric absorber technology.

The results, despite their significant uncertainties of up to10 %, show that gradual porosity geometries open up a promising field of research as they significantly improve the thermal efficiency of this type of absorber.

Data availability statement

Data supporting the results are restricted to the NEXTOWER project partners and cannot be shared at the time of writing.

Author contributions

J. Fernández-Reche: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft; **R. Monterreal**: Investigation, Resources, Draft review & editing; **A. Ávila-Marín**: Investigation, Resources, Writing – review & editing; **L. Ferrari:**, Absorbers design & manufacturing, Draft review & editing; **S. Gianella:** Absorbers design & manufacturing, Draft review & editing; **V.M. Candelario:** Absorbers design & manufacturing, Draft review & editing.

Competing interests

The authors declare that they have no competing interests.

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