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Cite as: AIP Conference Proceedings **2126**, 030066 (2019); https://doi.org/10.1063/1.5117578
Published Online: 26 July 2019

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Experimental and Numerical Evaluation of a Small Array of Ceramic Foam Volumetric Absorbers

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Abstract. This paper presents intermediate-scale experimental tests of a small 2 x 2 array of ceramic foam absorbers at CIEMAT-PSA (SSPS-CRS tower). Receiver air outlet temperatures of up to 900 ºC have been reached. The experimental activities are supported by CFD simulations in order facilitate the selection process of the foam geometry for the final CAPTure receiver prototype (333 kW thermal), which will be installed at the same location.

INTRODUCTION

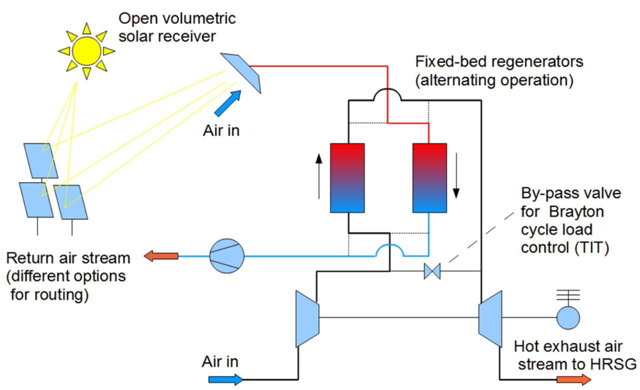
The CAPTure (Competitive SolAr Power Towers) project [1] resumes the investigation regarding volumetric solar absorbers working with atmospheric air as heat transfer fluid. This research project develops a prototype of a solar-driven hot air turbine powered by an open volumetric solar receiver, where the high temperature and the high heat flux part (solar receiver) is decoupled from the high pressure part (compressed air stream of the Brayton cycle) via an air-air regenerative heat exchanger (see Fig. 1 left-hand side). The project aims at applying a network of fixed-bed regenerative heat exchangers working in alternating modes (non-pressurized heating period, pressurized cooling period). The main objective of the project is to validate all key components that are required for the implementation of an innovative solar-powered combined cycle plant (topping Brayton cycle, bottoming Rankine cycle).

The solar absorber of the CAPTure receiver will be made of porous SSiC (pressureless sintered Silicon Carbide) foam (see Fig. 1, right-hand side), in contrast to honeycomb-type ceramic solar absorbers used previously [2, 3]. The solar receiver design is based on a modular approach, as suggested by previous research projects [2, 3], where the volumetric air solar receiver unit is typically composed of an array of cups, wherein each cup contains the solar absorber matrix. The modular design is required in order to adjust the mass flow locally (one orifice for each cup) according to the given solar flux map [4]. The aim is to achieve the same air outlet temperature for all cups. Unlike previous projects, the CAPTure solar receiver will be designed without air recirculation, i.e. there will be no return-air stream between cups in opposite direction to absorber flow. In previous projects, this return-air stream, coming from the power cycle (steam generator return air), was partially mixed with absorber inlet air (up to about 50% of air return ratio [2]), and the remaining part of low-temperature heat was lost to the environment. The motivations for designing the CAPTure receiver without air-recirculation are the following:

- The receiver design is considerable simplified since the air recirculation channels and the internal metallic structure are not needed any more. The receiver is thus cheaper to manufacture.
- The air-return temperature is defined by the compressor outlet temperature of the Brayton cycle (function of pressure ratio), which is significantly higher than achievable heat recovery steam generator stack temperatures of the conventional atmospheric air solar plant (Jülich type [5]).

SolarPACES 2018
AIP Conf. Proc. 2126, 030066-1–030066-8; https://doi.org/10.1063/1.5117578
Published by AIP Publishing. 978-0-7354-1866-0/$30.00

- The application of a low-temperature heat storage (e.g. thermocline air/rock TES) provides the possibility to use the low-temperature heat of the return air for boosting the bottoming Rankine cycle. Then, significantly less heat is lost to the environment.
- The overall plant efficiency can thus be improved, by (i) reducing the heat loss to the environment (see above point), and (ii) by operating the air blowers at ambient temperature (less power consumption).



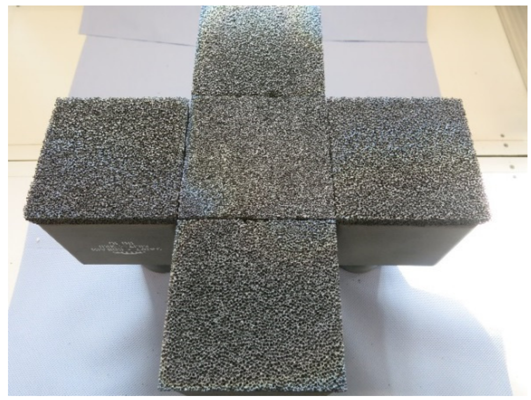
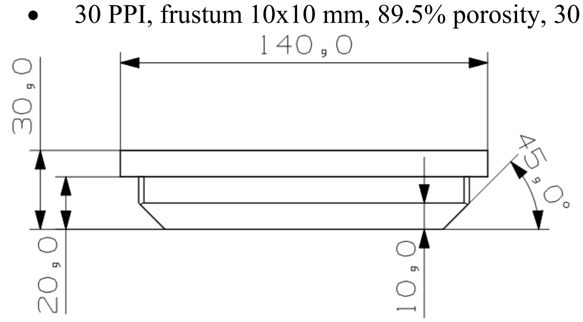


FIGURE 1. CAPTure air-air regenerative heat exchanger concept (left); The ceramic foam absorbers (right)

The foam absorber has been designed such that it covers the complete width of the cup (protection of the cup's front edges against direct incident solar flux) and provides sufficient total thickness in order to guarantee thermal equilibrium between air and solid at the rear of the absorber (see Fig. 1 and Fig. 2 right-hand side). In addition to this, a frustum shape (Fig. 2 right-hand side) at the rear of the absorber may homogenize the air speed over the entire cross section [6], leading to a homogenous absorber front temperature and thus better efficiency. In addition, the foam parameters as cell density and porosity have been optimized for thermal efficiency, with the result that the porosity should be as high as possible and the cell density should be around 30 PPI – pores per inch (flat optimum) [7]. From the point of thermal performance only, the absorber thickness shall not be larger than 30 mm; thicknesses above 20 mm appear fully sufficient [7]. Such low absorber thicknesses would also guarantee low pressure drops in the absorber, which is better for overall plant efficiency. Nevertheless, regarding mechanical stability aspects thicker foams may be required.

In order to facilitate the foam geometry selection process for the CAPTure solar receiver prototype, four promising foam parameter and geometry combinations have been selected for an intermediate-scale (2 x 2 array of cups according to Fig. 3, left-hand side) experimental test at the SSPS-CRS tower at the research facility PSA in the south of Spain. The four absorber configurations are as follows:

- 30 PPI, frustum 10x10 mm, 92.0% porosity, 65 mm thickness (A)
- 30 PPI, frustum 10x10 mm, 89.5% porosity, 65 mm thickness (B)
- 30 PPI, frustum 20x20 mm, 89.5% porosity, 65 mm thickness (C)
- 30 PPI, frustum 10x10 mm, 89.5% porosity, 30 mm thickness (D)



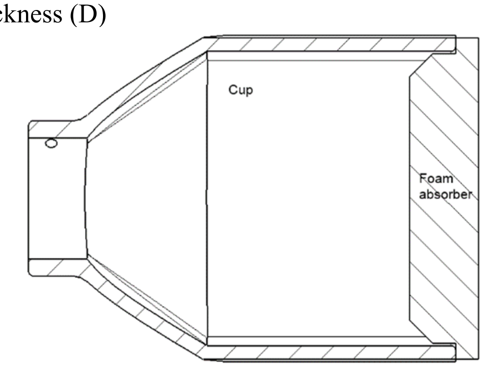


FIGURE 2. Foam geometry side view (left) with 30 mm total thickness and 10 x 10 mm frustum (D) – Cup and foam cross sectional view (right)

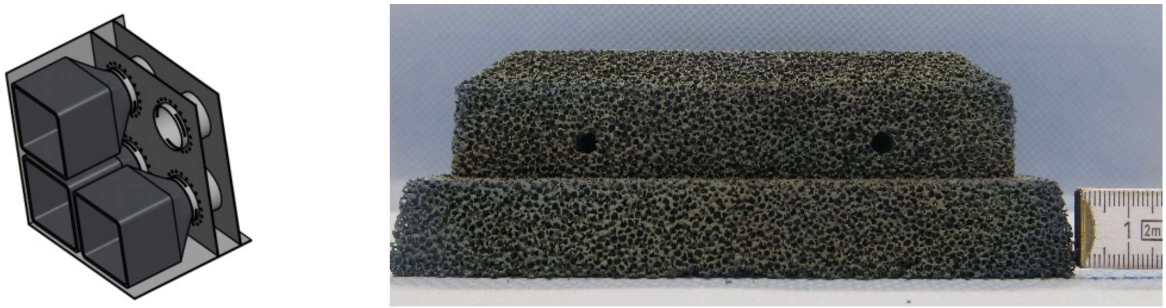


FIGURE 3. 3-D view of 2 x 2 cup array to be installed at the tower (left); Ceramic foam absorber side view (right)

The impact of the thickness (pressure drop) can be obtained by the comparison between absorber B and absorber D; the porosity influence can be studied by comparing absorber A with absorber B, and finally, the frustum geometry can be tested with absorber B and absorber C. 89.5% porosity has been chosen as lower value for the last three configurations because a smaller porosity step (down from 92%) is very difficult to achieve in the fabrication process. Also, for the last set (30 mm thickness only), a lower porosity (89.5%) is better for mechanical stability. Thus, in order to maintain comparability, the last three sets have the same lower value of porosity.

The intermediate-scale 2 x 2 array tests form the last experimental testing step and possibility for foam parameter selection before manufacturing and installing the final 333 kW thermal CAPTure receiver.

EXPERIMENTAL EVALUATION

Description of the Experimental Setup

The receiver (Fig. 3 left-hand side) for testing the 2 x 2 arrays has been installed at the SSPS-CRS tower at CIEMAT-PSA (see Fig. 4 left-hand side). In particular, the receiver is part of a calorimetric loop that should provide the required instrumentation to characterize the thermal behaviour of the different absorber configurations. Figure 4 shows the schematic of the implemented air loop. Air temperature, pressure and flow can be measured along the air loop in order to characterize the receiver's behaviour. Unfortunately, the accuracy of the installed measurement equipment was not high enough to provide a clear distinction between different absorber samples.

Therefore, this work's intention is to present the experimental work performed without a ranking of absorber samples. The key message is that the ceramic foam absorber samples have been successfully operated under relevant conditions at air outlet temperatures of up to 900 ºC.

Figure 5 shows the receiver box installed at the SSPS-CRS tower (outside and inside view without cups).

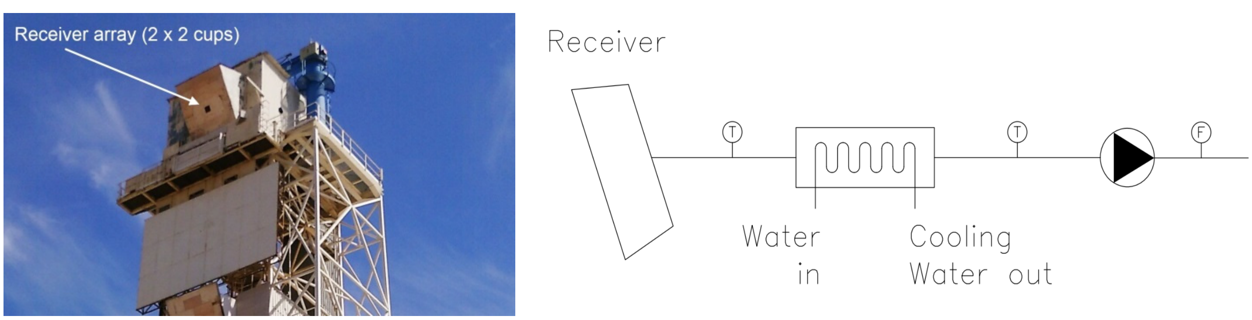


FIGURE 4. Picture of receiver and SSPS-CRS tower (left) – Air loop scheme for array testing installed inside the tower (right)

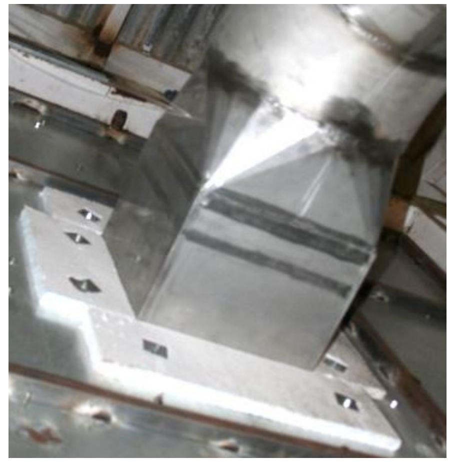


FIGURE 5. 2 x 2 array test loop installed at SSPS-CRS tower – front view without cups (left) – rear inside view (right)

Experimental Evaluation of Foam Absorber Samples

In the following, the experimental data of 2 testing days is shown in order to explain the experiments performed. Figure 6 displays data for a slightly overcast day and thus considerable DNI variations. The experiment started at 10:43 am. First, the cooling water flow in the heat exchanger (see Fig. 4) was activated (full constant flow). Next, the air blower was switched on and quickly ramped to full load (100%). Once the air flow through the experimental loop was established, the chosen heliostats were focused one after another in time intervals between 2 and 5 minutes. Note that only a fraction of the heliostat field (31 heliostats of the SSPS-CRS tower) was used. The heliostat operations (focusing and defocusing) are displayed with "plus" (green) and "minus" (red) signs. A "plus" means that a heliostat is focused at the given time. A "minus" means that a heliostat is defocused at the given time. Note that these heliostat operation entries only refer to the time axis. They are displayed staggered in y-direction (temperature) in order to avoid overlapping of the heliostat operation entries.

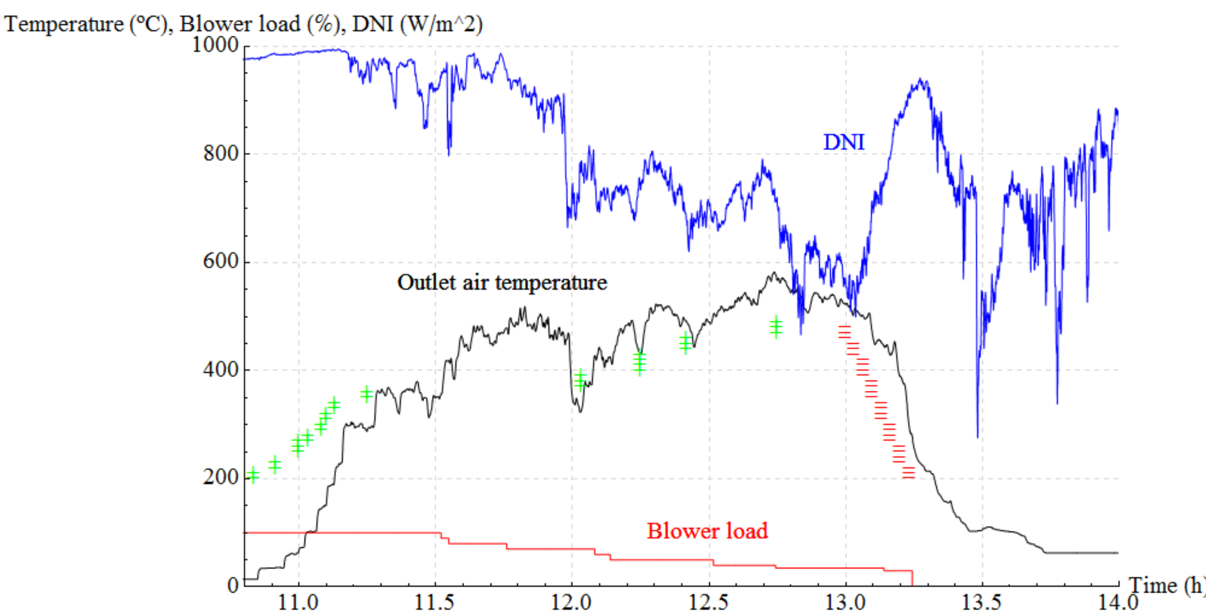


FIGURE 6. Experiment performed on the 7th of March 2018 – Receiver outlet air temperature (black), blower load (red) and DNI (blue); heliostat focused (+), heliostat defocused (-)

Figure 7 displays an experiment with low DNI variations. Here only 18 heliostats were used. However, the basic sequence of the experiment is very similar to the one explained before. First the cooling water was switched on. Then the blower was ramped to full load and the heliostats were focused as indicated by the green “plus” signs. Right before 11:00 am, all 18 heliostats were focused and remained tracking the sun until the defocusing started at about 02:15 pm. During the main part of the experiment (11:00 am until 02:15 pm), the blower load was varied between 100% and 50% load in order to achieve different mass flow rates and thus different air outlet temperatures according to the current DNI level. The highest receiver outlet temperature of about 900 ºC (lowest air flow) was achieved at about 12:45 pm. Then the blower load was increased step by step in order to decrease the operating temperature, being able to shut down the system in a safe manner.

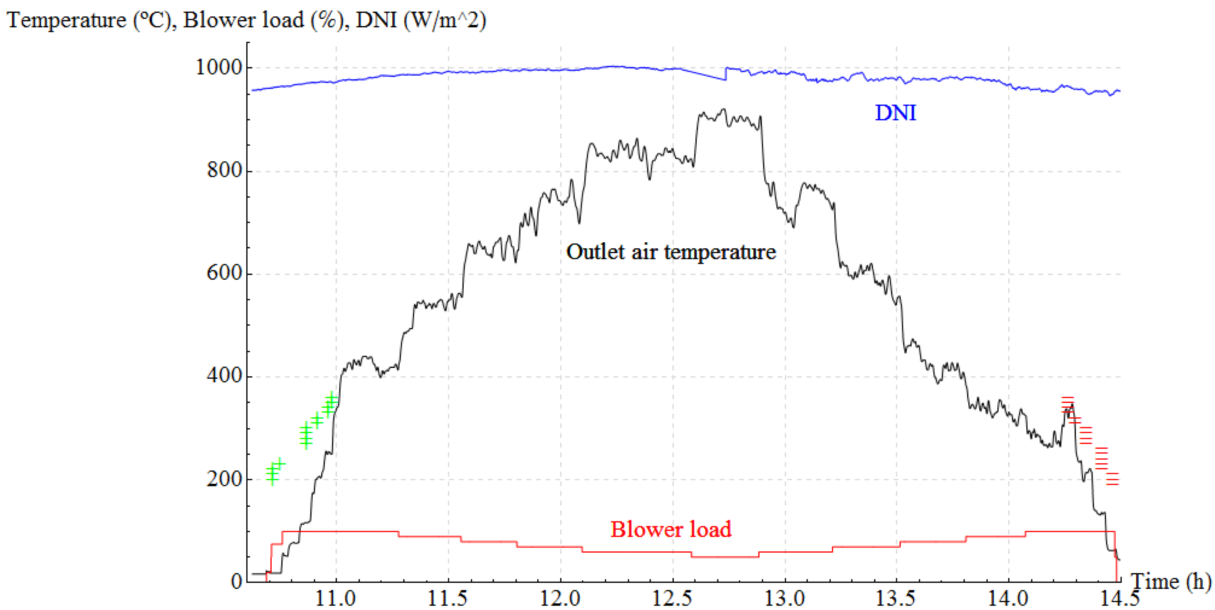


FIGURE 7. Experiment performed on the 9th of March 2018 – Receiver outlet air temperature (black), blower load (red) and DNI (blue); heliostat focused (+), heliostat defocused (-)

Unfortunately, no further conclusion can be drawn from the experimental results, because the installed measurement equipment was not suited to detect the small differences in absorber performance. Neither an approximate mean thermal receiver efficiency can be given because the incident solar flux was not measured due to constraints at the experimental facility. Nevertheless, it could be shown that the SSiC foam absorber samples, prepared by Fraunhofer IKTS, withstand operating conditions under highest temperatures. No fracture of the absorber samples was observed during the performed experiments.

Taking into account the lessons learned, the consortium will make sure that the thermal evaluation of the final CAPTure receiver prototype will be done with sufficient accuracy.

NUMERICAL EVALUATION

In order to support the selection process of the final absorber geometry for the CAPTure prototype (333 kW thermal), particularly because of the very limited experimental information obtained, numerical simulations have been performed for different rear shapes of the foam absorber (frustum – see Fig. 8). The aim was to find the best compromise between simple design (foam geometry manufacturing restrictions) and homogeneous flow velocity distribution. The fundamental aim of the rear absorber profile is to achieve a homogenous velocity profile across the cup’s aperture in order to guarantee homogenous cooling, avoiding hot areas at low flow velocities.

The cup (see Fig. 2) can basically be seen as a tube through which air is flowing. As commonly known from fluid mechanics, the flow needs a certain length until the velocity profile is fully developed. Furthermore, due to the non-slip condition at the duct walls, we get a parabolic velocity profile, having the highest velocity in the center of the tube. Thus, the velocity close to the cup’s walls will be lower than in the centre region and will cause hotter foam temperatures in zones close to the cup's walls (hot frame effect), which reduces the thermal efficiency. On the other hand, by using a frustum-shaped absorber (thus adjusting the flow resistance), a more homogenous velocity profile can be obtained leading to an almost uniform front surface temperature [6].

Figure 8 shows the foam geometries analysed numerically in order to support the geometry selection process.

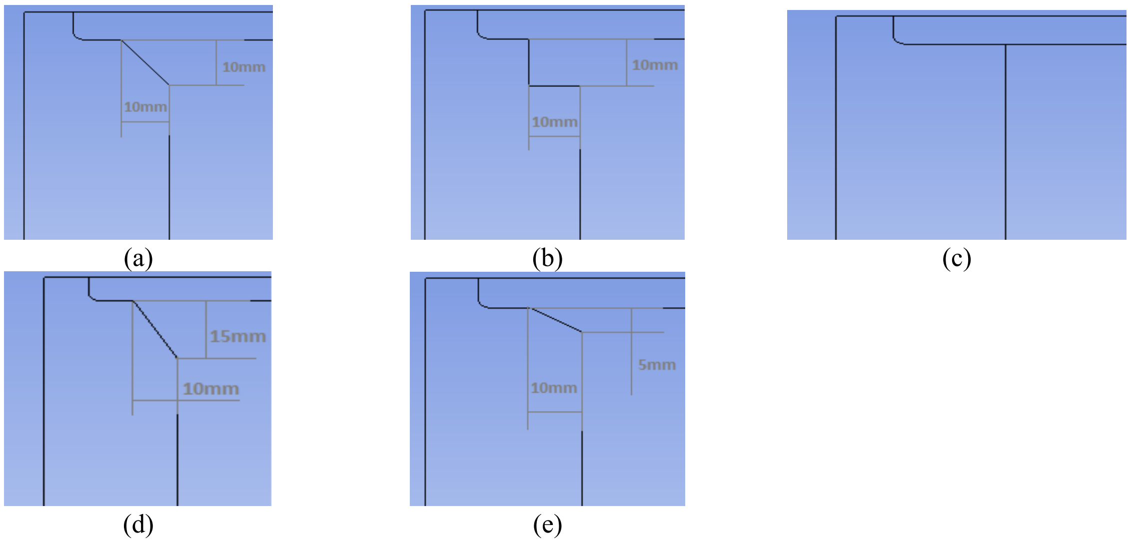


FIGURE 8. Foam rear geometries analyzed: (a) 10 x 10 frustum, (b) 10 x 10 square, (c) flat foam, (d) 15 x 10 frustum, (e) 5 x 10 frustum

The problem has been modeled applying the CFD software ANSYS Fluent. The k-epsilon turbulence model is selected for the calculation. The foam is modelled as a porous medium in Fluent. A local thermal non-equilibrium heat transfer model for the porous region is solved. Hence, two separate but coupled energy equations are solved, for the fluid and for the solid region. The developed model has been checked for grid-independent results and has been additionally validated against other simulation codes [8].

Simulation Results

Figure 9 displays the temperature contours of the absorber solid phase (ceramic material). Figure 10 displays the temperature contours of the absorber fluid phase (air). As can be seen in the figures, foam geometry (a) and (e) have the most homogenous temperature distributions.

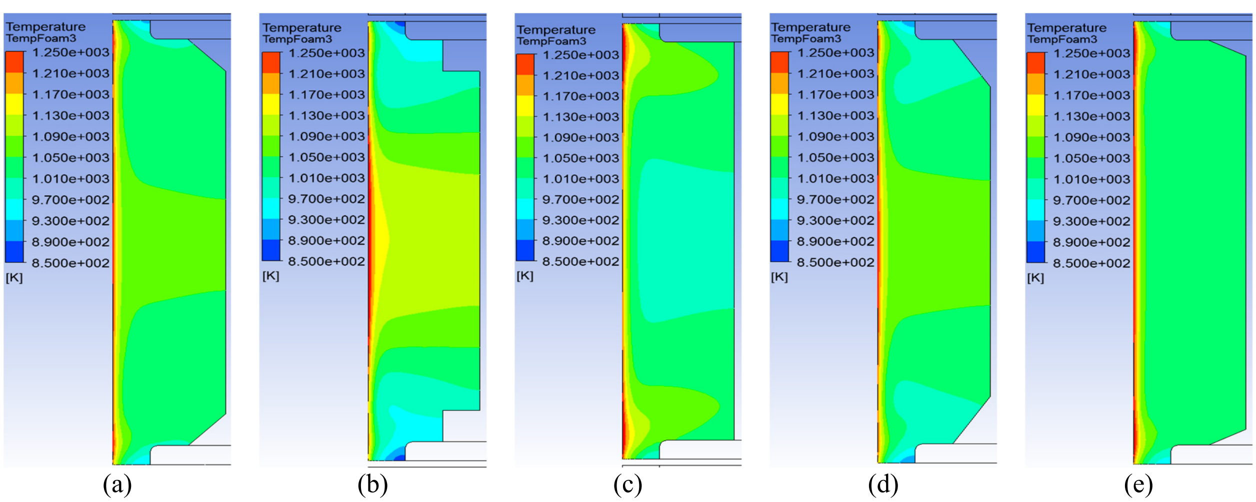
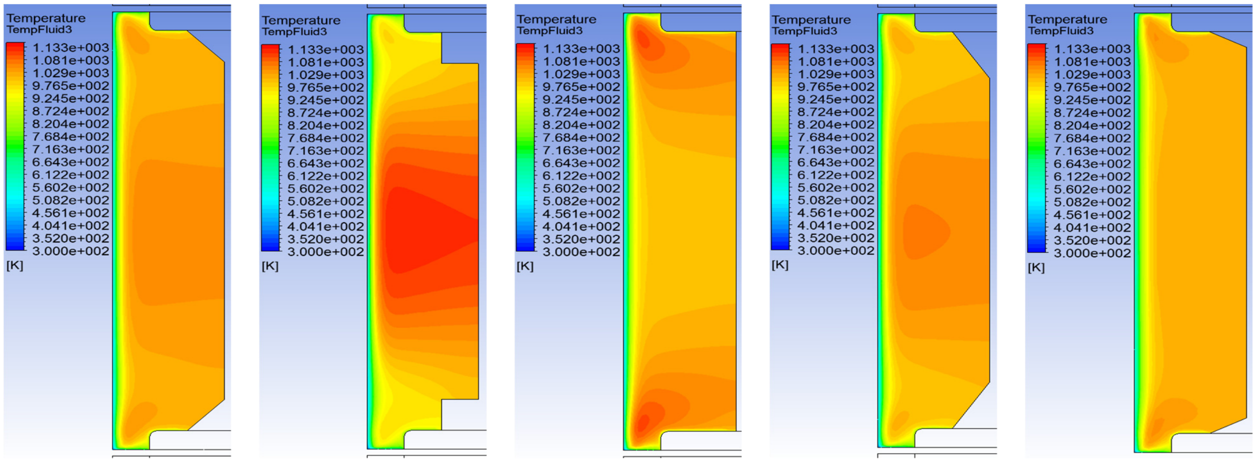


FIGURE 9. Contour plots of foam absorber solid phase (ceramic material) temperature



(a) (b) (c) (d) (e)

FIGURE 10. Contour plots of foam absorber fluid phase (air) temperature

When looking with more detail at the results of geometry (a) and (e), geometry (a) achieves theoretically little higher cup outlet temperatures and thus littler higher thermal efficiencies. However, the differences are very small and most probably not detectable in future experimental evaluations. Therefore, either geometry (a) or (e) could be chosen for the final receiver prototype. According to these numerical results and taking also into account that foam geometry (a) has already been evaluated experimentally, this foam geometry has been chosen for the final 333 kW thermal CAPTure receiver prototype (35 cups).

CONCLUSIONS

This paper presents a selection of research activities performed within the CAPTure project. On the one hand, it explains intermediate-scale experimental activities performed at the SSPS-CRS tower at CIEMAT-PSA. These tests of a small 2 x 2 array of solar absorbers were the last experimental testing step and possibility for foam parameter selection before manufacturing and installing the final 333 kW thermal CAPTure receiver at the same location. It could be shown that the ceramic foam absorber samples withstood operation under highest temperatures without fracture. Receiver air outlet temperatures of up to 900 ºC have been reached. However, no difference in absorber sample performance could be detected due to limited measurement capabilities.

Therefore, the final foam absorber geometry selection had to be also based on a numerical evaluation applying the CFD software ANSYS Fluent. Five different absorber shapes have been evaluated numerically, including different frustum shapes and also a simple flat foam geometry. According to the obtained results, geometry option (a) (frustum 10 x 10 mm, 30 mm thickness) has been selected for the final CAPTure receiver prototype.

ACKNOWLEDGMENTS

This work has received funding from the European Union's Horizon 2020 research and innovation program under the grant agreement No 640905.

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