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D6.1 - Small-scale experimental evaluation results of advanced volumetric absorber modules

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Summary

This document describes the testing devices, methodologies and results of the ASTERIX-CAESar small-scale solar absorber prototypes installed at CIEMAT-PSA and at IMDEA Energy. The principal aim of this testing campaign was to evaluate the performance of a novel manufacturing route for open cellular Silicon Carbide foam with less energy consumption and lower cost. The new aspect of the absorber is a modified manufacturing method that has the objective of reducing cost and energy consumption. By changing the composition of the material, a double layer coating of the foams without intermediate pyrolysis can be used to increase the mechanical properties of the foam and its stability against oxidation.

Additionally, in order to further reduce receiver costs, the objective of ASTERIX-CAESar is to increase the solar absorber module size from 14 x 14 cm (CAPTURE project module size) to above 20 x 20 cm.

Larger sizes of foam tiles are more difficult to handle and will likely cause manufacturing problems. The solar furnace tests at CIEMAT-PSA were therefore done with small samples (12 cm x 12 cm), evaluating 2 recipes, the original CAPTURE project recipe (R1), and the new less energy intensive recipe (R2).

At CIEMAT-PSA, the small-scale solar receiver experiments were performed at the solar furnace at an existing thermal characterization loop.

Next, as second step, after having confirmed the new recipe's performance at small size, larger foam samples (up to 25 x 25 cm) were tested at IMDEA-Energy, at its solar tower facility.

The objective of the two testing campaigns described in this deliverable is the characterization of the open volumetric air receiver before its installation in the medium-scale prototype at CIEMAT-PSA during the last period of the ASTERIX-CAESar project.

Overall, the PSA campaign provided a robust and coherent dataset supporting the reliability of the new absorber designs and the validity of the test methodology. It can be confirmed that the new recipe (R2) behaves very similar to the original CAPTURE foam, that was successfully tested back in 2020.

Unfortunately, at larger sizes, the new manufacturing route showed severe issues leading to blocked pores and foam samples that were not working correctly. Several foam samples were destroyed during the test runs and finally it was decided to increase pore size (from 30 PPI to 20 PPI). The increase in pore size solved the problem and foam samples of 25 x 18 cm size were successfully tested at IMDEA in early summer 2026.

The conclusion is that when increasing pore size, the issue of blocked pores can be handled, also for increased absorber tile size. The final solar absorber tile size of the main ASTERIX-CAESar prototype will be 25 x 18 cm (Note that the rectangular shape is determined by the existing receiver casing). Its performance has been successfully tested at single model level at the tower of IMDEA. The upcoming final receiver tests should further validate the oxidation resistance during the experimental activity in the final project year.

Nomenclature

ACRONYM	DESCRIPTION
KPI	Key performance indicator
CT	Computed tomography
CCD	Charge-coupled device

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1 Introduction

This document describes the specifications of the ASTERIX-CAESar small-scale prototypes installed and tested at CIEMAT-PSA as well as at IMDEA Energy institute. The objective of this activity is the thermal and optical characterization of the solar receiver at small scale before its installation in the mid-scale prototype at the CIEMAT-PSA tower in Almería. The results of these tests will serve as an intermediate step in the validation of the receiver, allowing its viability to be demonstrated in a relevant environment before its installation at a larger scale.

The principal aim of this testing campaign is to evaluate the performance of a novel manufacturing route for open cellular Silicon Carbide foam with less energy consumption and lower cost. The new aspect of the absorber is a modified manufacturing method that has the objective of reducing cost and energy consumption. By changing the composition of the material, a double layer coating of the foams without intermediate pyrolysis can be used to increase the mechanical properties of the foam and its stability against oxidation.

Additionally, to further reduce receiver costs, the objective of ASTERIX-CAESar is to increase the solar absorber module size from 14 x 14 cm (CAPTure project module size) to above 20 x 20 cm.

Larger sizes of foam tiles are more difficult to handle and will likely cause manufacturing problems. The solar furnace tests at CIEMAT-PSA is therefore done with small samples (12 cm x 12 cm), evaluating 2 recipes, the original CAPTure project recipe (R1), and the new less energy intensive recipe (R2).

At CIEMAT-PSA, small-scale solar receiver experiments of single modules are planned at the solar furnace at an existing thermal characterization loop.

On the other hand, at IMDEA-Energy, a small-scale solar receiver unit will be tested at an experimental high-flux solar tower plant.

This document is organized as follows:

- Section 2 describes the objectives of this testing campaign and the indicators used to evaluate it, as well as a description of the geometry and characteristics of the receiver.
- Section 3, which is split in two subsections, describes the solar absorber testing device and methodology first, at the solar furnace at CIEMAT-PSA in Almería and then, at the high-flux tower plant at IMDEA Energy in Madrid.
- Section 4, following the previous section, is also split into two subsections, one for each of the test facilities, and shows the results obtained.
- Section 5 summarizes the results of the previous sections and brings together the conclusions of the test campaign.

2 Experimental objectives and approach

2.1 General objectives of small-scale tests

The small-scale experimental campaign performed at the CIEMAT-PSA solar furnace aimed to validate, at the level of a single absorber cup, the thermal and optical performance of the advanced volumetric absorber modules developed within Work Package 2. These tests represented the first experimental step in the technology validation chain of the ASTERIX-CAESar project, bridging the gap between material characterization and module-scale receiver testing.

The primary objectives were:

- To quantify the aerodynamic characteristics of the cup geometry, including the effect of outlet orifice size on flow behaviour in the absence of solar flux.
- To evaluate the thermal behaviour of individual absorber prototypes under highly concentrated solar flux, determining their efficiency, temperature distribution, and

operational stability.

- To compare two manufacturing routes and multiple geometric configurations of the volumetric absorber, in order to identify which designs provide the best combination of thermal performance and structural robustness.
- To assess the optical properties (absorptance and emittance) of the materials before and after solar testing, identifying any changes induced by thermal cycling or high-temperature operation.

Together, these activities provided a comprehensive evaluation of absorber behaviour at small scale, enabling a first screening of candidate designs before proceeding to validation at module level.

On the other hand, the test campaign performed at IMDEA Energy solar tower aims to validate the solar absorber at a larger size. Up to now, the typical absorber module size has not been larger than 15 cm of width (square shaped). The ASTERIX-CAESAR project intends to increase this size to about 25 cm, with the objective to reduce costs. The main objective of the tests at IMDEA is to test such a large-size absorber cup (25x25 cm) and determine its thermal performance and the durability. This test campaign has been designed as an intermediate step between the initial tests carried out during task 6.1 at CIEMAT-PSA and the trials of the complete prototype that will be conducted during the final year of the project.

The primary objectives were:

- To evaluate the thermal performance of a large-size receiver working under more realistic radiative conditions receiving concentrated radiation directly from a heliostat field.
- To validate mechanical integrity of the receiver components (foam and cup) against peak fluxes above $1.5 \text{ MW}_{\text{th}}/\text{m}^2$ and mean fluxes of $800 \text{ kW}_{\text{th}}/\text{m}^2$.
- To test and compare thermal and mechanical performance of the second version of the foams, manufactured with the same parameters but using a cheaper methodology reducing the final cost of the receiver, with the previous ones obtained by CIEMAT-PSA during task 6.1.

These activities will enable the receiver to be validated under real operating conditions prior to its installation in the complete prototype.

2.2 Key Performance Indicators

The definition of Key Performance Indicators (KPIs) provides a quantitative framework to evaluate the experimental results obtained in the small- and medium-scale testing campaigns.

Given the different scales, objectives, and instrumentation of the two facilities, the KPIs are presented separately for the CIEMAT-PSA solar furnace (Task 6.1) and the IMDEA Energy solar tower (Task 6.2). This separation ensures that the performance assessment is fully aligned with the specific measurement capabilities and operational conditions of each experimental setup.

2.2.1 CIEMAT-PSA Key Performance Indicators (Task 6.1)

The KPIs for the CIEMAT solar furnace campaign were selected to quantify the aerodynamic behaviour, thermal efficiency, and optical performance of individual absorber cups tested under highly concentrated solar flux and are presented in Table 1

Table 1: CIEMAT-PSA key performance indicators

Test type	Parameter	Symbol / Unit	Description / Measurement Method
-----------	-----------	---------------	----------------------------------

Cold flow tests	Air mass flow rate	$\dot{m}_{\text{air}}$ (kg·s ⁻¹)	Determined from flow-meter readings. Used to quantify the aerodynamic resistance of the absorber cup for different outlet orifice diameters and blower speeds.
Thermal tests	Useful thermal power gained by air	P_{useful} (kW)	Calculated from the air–water heat exchanger calorimetry, representing the net heat transferred from the absorber to the air.
	Thermal efficiency	η_{th} (%)	Ratio of the useful thermal power absorbed by the air to the total incident solar power on the aperture, derived from CCD flux images calibrated with a Gardon radiometer.
Optical tests	Hemispherical solar absorptance	$\alpha_{s,h}$ (–)	Measured with a Perkin Elmer Lambda 1050 spectrophotometer (280–2500 nm). Indicates the fraction of incident solar energy absorbed by the absorber material.
	Hemispherical thermal emittance	ε_{th} (–)	Determined with a Perkin Elmer Frontier FT-IR spectrophotometer (2.5–16 μm) at temperatures up to 800 °C. Characterizes radiative losses from the absorber surface.

These indicators provided a consistent basis for comparing absorber designs and materials under controlled small-scale conditions.

2.2.2 IMDEA-Energy Key Performance Indicators (Task 6.2)

The KPIs for the IMDEA Energy solar tower test campaign were selected to quantify the thermal efficiency and to validate the mechanical integrity of the mid-scale receiver under high flux and are presented in Table 2.

Table 2. IMDEA Energy test campaign key performance indicators

Parameter	Symbol / Unit	Description / Measurement Method
Maximum exposed heat flux	Q_{rad} (kW/m ²)	Determined from the incident solar power distribution on the aperture, derived from CCD flux images.
Useful thermal power gained by air	P_{useful} (kW)	Calculated from the air–water heat exchanger power balance, representing the net heat transferred from the absorber to the air.
Thermal efficiency	η_{th} (%)	Ratio of the useful thermal power absorbed by the air to the total incident solar power on the aperture, derived from CCD flux images.

2.3 Overview of absorber prototypes

At IKTS a set of foam test samples have been prepared, representing two generations of ceramic foam prepared of pressure-less sintered silicon carbide. The first group labeled with “R1” was prepared according to the technological approach developed within the European Project CAPTURE [1]. This kind of foam recipe and manufacturing technology was tested intensively in a large-scale demonstrator during that project. On that account, the “R1”-samples represent the reference material. The second group of foams labeled with “R2” differs slightly in the

composition of the material itself and in the preparation route, which is less energy consuming and therefore cheaper and more environmentally friendly. Since the foams of the “R2” material showed good performance during CAPTure-testing, it was aimed to realize similar geometrical properties of the foams also with the new foam generation “R2”. In the following tables basic geometrical parameters of both recipes are compared, indicating that almost the same properties can be reached with the new processing route and recipe. Some samples have been drilled to enable fastening via pins in the cup.

Table 3: Foam samples and parameters for solar

Sample	Cell size ppi	Weight g	Length mm	Width mm	Height mm	Total porosity %	Fixing
R1-169	30	161.6	120.0	119.4	30.0	86.8	drill holes
R1-165	30	122.0	120.1	120.0	30.1	90.1	drill holes
R1-164	30	154.1	120.1	120.3	30.1	87.4	drill holes
R1-168	30	152.7	120.1	120.0	30.1	87.5	
R1-166	30	146.2	120.0	120.0	29.5	88.1	drill holes
R1-170	30	147.9	119.8	119.9	30.1	87.9	
R1-167	30	142.2	120.0	120.0	29.9	88.4	
R1-163	30	109.5	120.0	120.0	30.1	91.1	drill holes
R2-2	30	147.7	120.1	120.0	30.0	88.0	drill holes
R2-4	30	153.2	119.9	120.0	30.2	87.5	drill holes
R2-3	30	148.3	119.5	119.8	30.1	87.9	
R2-1	30	138.7	120.2	120.2	30.1	88.7	
R2-7	30	154.2	120.0	120.1	30.1	87.4	drill holes
R2-5	30	120.9	120.1	120.1	30.1	90.1	
R2-8	30	119.3	120.0	120.0	30.2	90.3	drill holes
R2-6	30	118.7	120.0	119.9	30.2	90.3	drill holes

The estimated specific surface area of the foams, with a mean cell size of around 1300 μm , is between 2500 to 3000 m^2/m^3 . The expected accessible porosity (cell porosity) is in the range of 81-84 %.

In addition to the geometrical characterization, a computed tomography (CT) scan and analysis has been performed at IKTS leading to the results as indicated in Table 4. These values might be used for modelling the behavior of such foam structures.

Table 4: CT results of foam sample groups R1 and R2

Average geometrical values	unit	R1	R2
Cell diameter	dc (μm)	1470	1680
Strut diameter	ds (μm)	210	185
Window diameter	dw (μm)	490	560
Porosity total	ε (%)	88.4	88.8
Cell porosity (accessible)	ε_c (%)	85.0	85.4
specific surface area	Sv (m^2/m^3)	2322	2017

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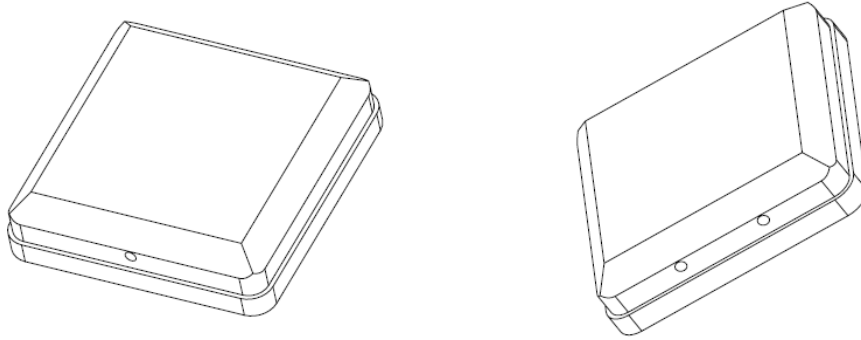


Figure 2: Solar absorber foam dimensions for solar testing

2.5 Overview of orifice dimensions

The air mass flow for each absorber module needs to be adjusted to achieve similar cup outlet temperatures amongst each other due to the non-homogeneous solar flux profile at full receiver scale. To study the impact of orifice diameter on air flow and absorber cooling, three orifice dimensions have been defined (60 mm, 40 mm and 30 mm diameter – see Figure 3).

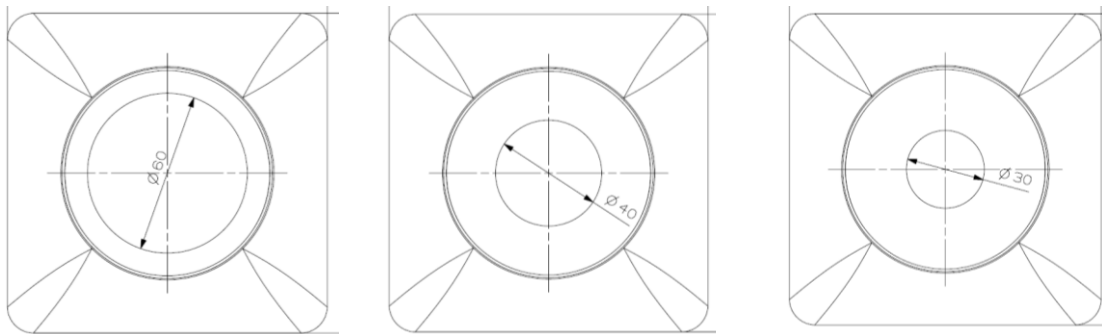


Figure 3: Orifice dimensions for solar furnace testing

The following figure shows manufactured absorber modules and foams. The absorber cups were manufactured by partner WPS using a lightweight and highly temperature resistant ceramic composite material [2].

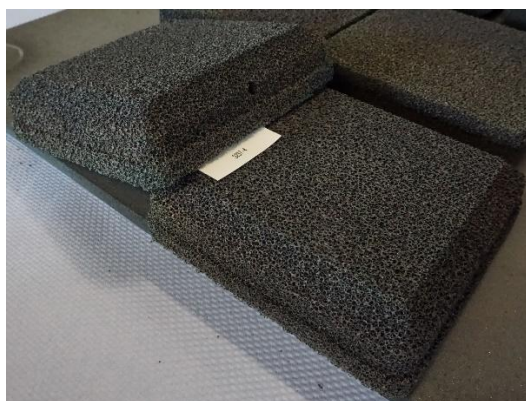




Figure 4: Manufactured samples for solar furnace testing

3 Experimental facilities and methods

The experimental activities carried out within the project rely on advanced solar research infrastructures operated by the project partners. These facilities enable testing under relevant conditions for high-temperature concentrated solar technologies. The experimental setups are designed to evaluate materials, components, and system configurations under controlled and reproducible conditions, supporting both validation of numerical models and generation of data for performance assessment. In particular, two main infrastructures have been employed: the Solar Furnace at CIEMAT-PSA at 10 kW_{th}, and the IME Tower Test Loop (IME-CENER) at 20 kW_{th}, which together provide complementary capabilities for high-flux solar irradiation, thermal management, and system integration testing.

3.1 Solar Furnace at CIEMAT-PSA

3.1.1 Description of the facility

The principal aim of the planned experiments is to evaluate the thermal performance of specific absorber samples in terms of thermal efficiency, fluid flow performance and evolution of the optical properties. To do so, the absorber samples will be exposed to concentrated solar flux and a thermal air loop will force cooling air through the samples to simulate the operation of a full-scale volumetric solar receiver. Figure 5 shows a cross-sectional view of the CAPTURE receiver prototype (300 kW_{th}), highlighting one absorber module (cup). Figure 6 shows the open volumetric air receiver concept and a scheme of one representative absorber module.

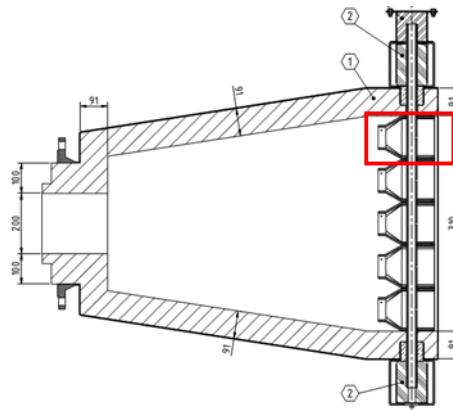


Figure 5: CAPTURE receiver prototype drawing with one absorber module selected

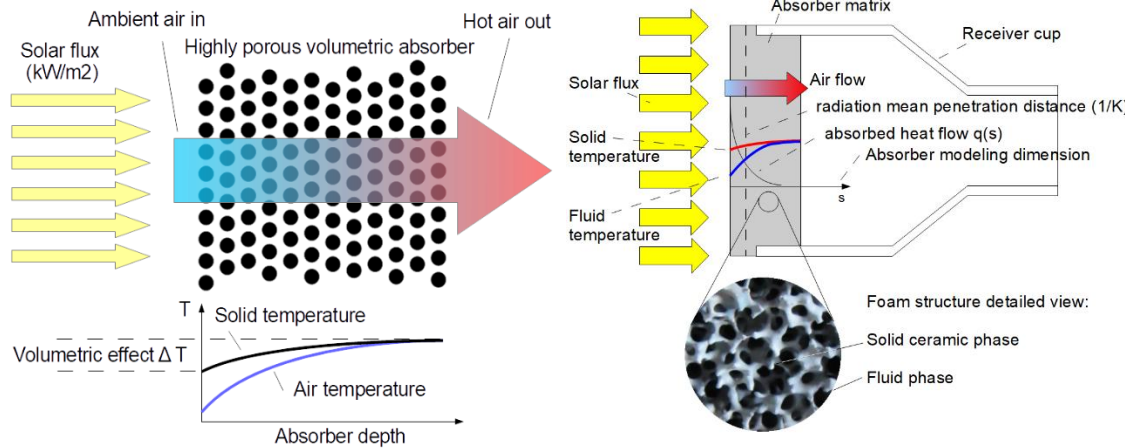


Figure 6: Open volumetric air receiver working principle and ideal temperature profiles (left); Absorber module (cup) exposed to incident solar flux (right)

A schematic view of the CIEMAT-PSA solar furnace is shown in Figure 7. The facility provides highly concentrated and precisely controllable solar flux, enabling small-scale testing of receiver materials and components under relevant operating conditions.

For this campaign, a dedicated thermal air loop was designed to reproduce the boundary conditions of a volumetric air receiver at small scale (Figure 8).

The absorber module is mounted at the inlet of a ceramic holder, through which ambient air is forced by a variable-speed blower. The loop includes an air-water heat exchanger for cooling and a flowmeter. The solar flux is regulated through a movable shutter mechanism, enabling adjustment of the incident power and maximum flux level during operation.

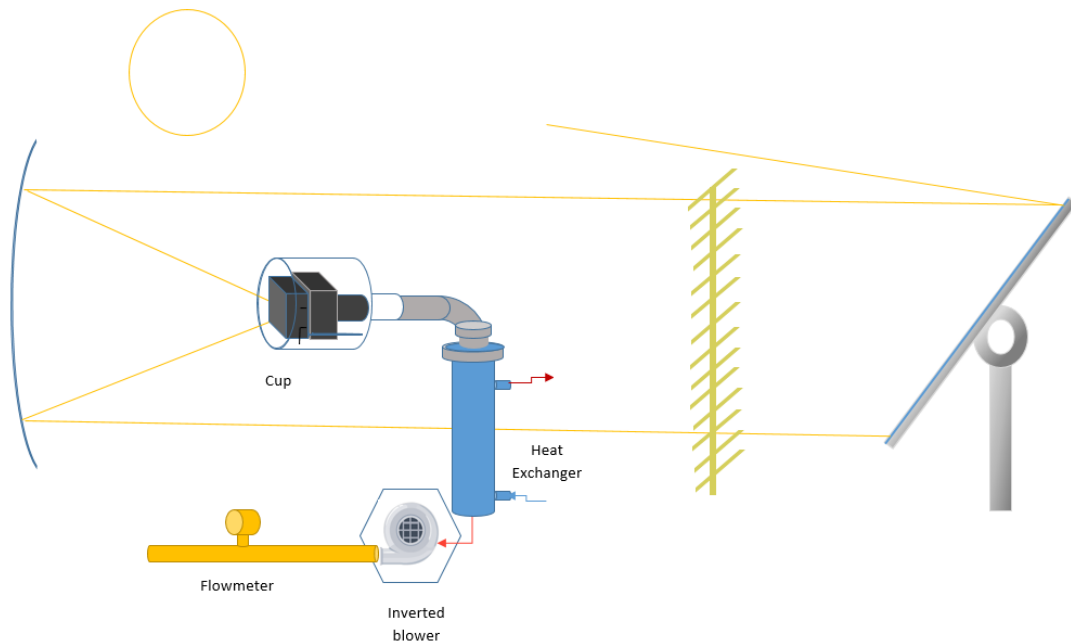


Figure 7: Solar of the CIEMAT-PSA solar furnace used for small-scale absorber testing



Figure 8: Solar furnace thermal air loop (sample holder, air water heat exchanger and air blower)

3.1.2 Testing Methodology

The experimental work performed at the PSA solar furnace was divided into three main phases, each aimed at characterizing specific aspects of the volumetric absorber's performance:

1. **Cold Flow Tests:** These preliminary tests were conducted without solar irradiation to evaluate the aerodynamic behaviour of the absorber module and the pressure losses generated across the sample. The influence of the outlet orifice size on the flow resistance was investigated by testing a single absorber cup with three outlet configurations: circular openings of 60 mm, 40 mm, and 30 mm diameter. Each configuration was tested under different blower speeds (25%, 50%, 75%, and 100%) allowing the relationship between the air mass flow and the blower speed through the cup with different orifices.
2. **Thermal Performance Tests:** In this second phase, the absorber modules were evaluated under solar irradiation to determine their thermal efficiency. A single absorber cup equipped with a 60 mm outlet orifice was used for these tests. A total of nine different absorber samples, out of the ten initially prepared, were tested following the methodology described in Section 2, as one sample was accidentally damaged during handling before testing. The solar tests were performed under controlled air flow rates and solar flux conditions, representative of real operating environments in volumetric receivers. These tests provided key data for comparing the relative thermal performance and durability of the different absorber materials.
3. **Optical Properties:** Evaluation Finally, the absorbers' optical properties, mainly absorbance and emittance, were measured before and after the solar tests. This preliminary analysis aimed to identify potential changes in surface properties induced by high-temperature exposure and oxidation during operation. Such measurements provide valuable insight into the long-term optical stability and potential degradation mechanisms of the absorber materials.

The combination of these three complementary test phases enabled a comprehensive evaluation of the absorber modules, covering their aerodynamic, thermal, and optical behaviour under representative operating conditions. The following section describes in detail the instrumentation and data processing methods used to evaluate and analyse the experimental results.

3.1.3 Sensors and methodology used for the evaluation of the results

The experimental setup was instrumented to record the key thermodynamic and optical parameters required for the characterization of the absorber modules. Two main measurement systems were implemented:

- one dedicated to the Cold Flow and Thermal Tests,
- and another for the Optical Properties Characterization.

3.1.3.1 Cold Flow and Thermal Tests

The instrumentation system used during the Cold Flow and Thermal Performance tests is illustrated in Figure 9. It was designed to monitor the main thermal and fluid-dynamic variables of the air loop and the absorber module.

The system includes the following components:

1. Temperature measurements (TK01–TK19): A set of K-type thermocouples was installed along the air circuit and on the absorber module to measure local air and surface temperatures.
Sensors TK01–TK03 recorded the inlet air temperature, while TK15–TK19 were located within the absorber cup to capture the internal temperature gradients under solar flux. Additional thermocouples (TK04–TK12) were placed along the duct to measure the outlet temperature and assess convective heat transfer performance.
2. Pressure measurements (PT005, PT101, PT102): Static and differential pressure transducers were used to determine the air pressure drop across the absorber and to monitor loop operating conditions, especially across the air–water heat exchanger.
3. Air mass flow measurement (FT002, FT002m): The cooling air flow rate was measured with a thermal mass flowmeter (model FCI FLUID) rated for operation up to approximately 450 °C and 36 L/min nominal capacity.
4. Solar flux measurement (RA010): A calibrated radiometer located near the focal plane was used to measure the incident solar flux on the absorber surface. This input was used to determine the absorbed power and compute instantaneous receiver efficiency.
5. Blower control and monitoring (RLG38 T2 – SC019 %, TK010–TK012): The main air blower supplied ambient air to the loop. Its rotational speed (SC019 %) was adjusted to reach the desired flow rate, while thermocouples TK010–TK012 monitored the air temperature at the blower outlet and along the return line to detect any preheating effects.

All sensors were connected to a multi-channel data acquisition system operating at 1 Hz sampling frequency. Each channel was calibrated and logged continuously during tests. Data were post-processed using in-house scripts to compute instantaneous and averaged values of temperature, pressure, and flow.

The estimated measurement uncertainties were: $\pm 1.0\text{--}1.5$ K for temperature, ± 1 % for mass flow, and ± 3 % for flux determination. The overall uncertainty in the computed thermal efficiency was below $\pm 3\text{--}5$ %, these values are summarized in Table 5.

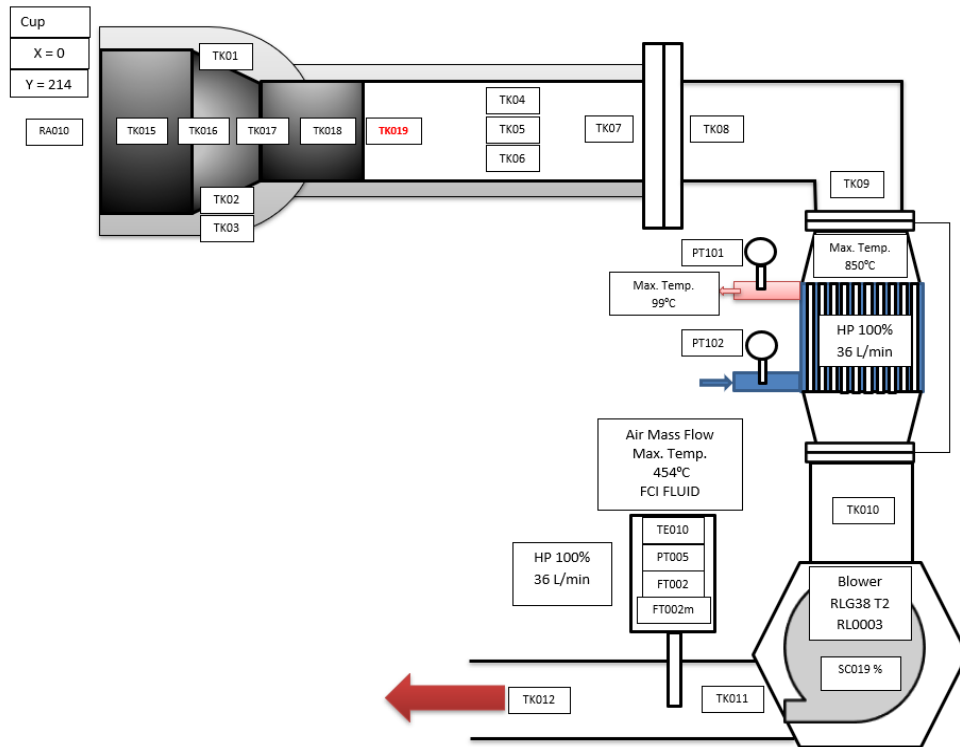


Figure 9: Schematic of the solar furnace thermal loop and sensor layout used during absorber testing

3.1.3.2 Optical Properties Characterization

The optical characterization of the absorbers samples was performed to evaluate the potential changes in reflectance, absorptance, and thermal emittance before and after solar testing.

The analysis consisted of measuring the hemispherical reflectance over a wide spectral range, converting the reflectance data into solar-weighted absorptance and thermal emittance values. Three initial measurements (before solar exposure) and nine final measurements (after solar testing) were carried out on each sample to ensure reproducibility.

1) Hemispherical Reflectance ($\rho_{s,h}$) and Absorptance ($\alpha_{s,h}$)

The hemispherical reflectance was measured using a Perkin Elmer Lambda 1050 UV/VIS/NIR spectrophotometer (Figure 10). Measurements were performed in the wavelength range of $\lambda = 280 - 2500$ nm, at 5 nm intervals, and with an incidence angle of $\theta_i = 8^\circ$. The measurement spot size in the spectrophotometer was approximately 9×17 mm².



Figure 10: Perkin Elmer Lambda 1052 spectrophotometer used for hemispherical reflectance measurements

Following ASTM Standard E903-82, the solar-weighted hemispherical reflectance $\rho_{s,h}$ was calculated by weighting the spectral hemispherical reflectance $\rho_{\lambda,h}$ with the solar direct irradiance $G_b(\lambda)$ on the Earth's surface, according to equation (1).

$$\rho_{s,h} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} \rho_{\lambda,h} \cdot G_b(\lambda) d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} G_b(\lambda) d\lambda} \quad (1)$$

where $\lambda_{min} = 280 \text{ nm}$ and $\lambda_{max} = 2500 \text{ nm}$.

The solar weighted hemispherical absorptance, $\alpha_{s,h}$, was then derived from the reflectance data using equation (2):

$$\alpha_{s,h} = 1 - \rho_{s,h} \quad (2)$$

This parameter provides an estimation of the fraction of incident solar energy effectively absorbed by the material under direct solar irradiation.

2) Thermal Emittance (ϵ_{th})

The thermal emittance of the absorber materials was determined using a Perkin Elmer Frontier FT-IR spectrophotometer (Figure 11). The spectral reflectance measurements were extended to the infrared range (2.5–16 μm) with 4 nm intervals. The measurements were performed at an incidence angle of 12° using an integrating sphere (diameter 76.2 mm) coated internally with Infragold. The sample aperture diameter was 20 mm.



Figure 11: Perkin Elmer Frontier FT-IR spectrophotometer used for infrared reflectance measurements

The thermal emittance, ϵ_{th} , at a given absorber temperature T was calculated using equation (3), by integrating the non-reflected spectral fraction $[1 - \rho_{\lambda,h}]$ weighted with the blackbody spectral emittance $M_{bb}(\lambda, T)$ as shown in equation (4):

$$\epsilon_{th}(T) = \frac{\int_{\lambda_{min}}^{\lambda_{max}} [1 - \rho_{\lambda,h}] \cdot M_{bb}(\lambda, T) d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} M_{bb}(\lambda, T) d\lambda} \quad (3)$$

$$M_{bb}(\lambda, T) = \frac{2\pi hc^2}{\lambda^5 \left[e^{\left(\frac{hc}{\lambda kT} \right)} - 1 \right]} \quad (4)$$

Where:

- $M_{bb}(\lambda, T)$ is the blackbody spectral emittance in $W/(m^2 \cdot \mu m)$
- h is the Planck's constant ($6.63 \cdot 10^{-34} J \cdot s$)
- c is the speed of light in vacuum ($2.997 \cdot 10^8 m/s$)
- k is the Boltzmann's constant ($1.38 \cdot 10^{-23} J/K$).

The integration was performed for the wavelength range $\lambda_{min} = 300 \text{ nm} - 16 \mu m$, combining both UV/VIS/NIR and IR data to ensure full spectral coverage.

The thermal emittance of the absorber samples was evaluated for temperatures of 25 °C, 600 °C, 700 °C and 800 °C.

3.1.4 Methodology used for the evaluation of Data Processing

The experimental data recorded during the solar furnace campaign were processed using dedicated analysis scripts developed at CIEMAT-PSA.

The evaluation focused on determining the air mass flow rate, thermal power absorbed by the air, and the resulting thermal efficiency of each absorber configuration.

Given the specific characteristics of the experimental setup, a combination of direct measurements and indirect calorimetric estimations was applied to improve the reliability of the results.

3.1.4.1 Steady-state identification

Steady-state conditions were defined based on the stability of the water temperature difference across the air–water heat exchanger.

Each test was considered quasi-stationary when the temperature difference between the hot and cold water sensors remained constant for a sufficiently long period (typically some minutes), depending on the particular absorber and operating conditions.

Within these intervals, instantaneous values were acquired every second and averaged over 30–60 s to obtain representative values for all measured quantities.

3.1.4.2 Determination of air mass flow rate

Initial calculations based on the air-side flow meter indicated inconsistencies: the thermal power estimated from air measurements was significantly lower than the power transferred to the water in the heat exchanger. This discrepancy suggested a systematic error in the air mass flow measurement, possibly caused by calibration drift or changes in air density at high temperature.

To overcome this limitation, an indirect determination of the air mass flow rate, $\dot{m}_{a,inf}$, was performed using the calorimetric balance of the heat exchanger, under the assumption that all the heat gained by the air in the receiver was subsequently transferred to the cooling water with equation (5):

$$\dot{m}_{a,inf} = \frac{\dot{m}_w \cdot c_{p,w} \cdot (T_{o,w} - T_{i,w})}{c_{p,a} \cdot (T_{o,a} - T_{i,a})} \quad (5)$$

where $c_{p,a}$ and $c_{p,w}$ was obtained from correlations available in the literature as a function of the

mean air temperature.

This approach provided consistent values of air mass flow and ensured energy balance between the air and water sides.

3.1.4.3 Calculation of absorbed power and thermal efficiency

The useful thermal power transferred to the air inside the receiver was determined as follows in equation (6):

$$Q_a = \dot{m}_{a,inf} \cdot c_{p,a} \cdot (T_{o,aver} - T_{amb}) \quad (6)$$

where $T_{o,aver}$ corresponds to the average temperature measured by the near-exit thermocouples (TK04–TK06), and T_{amb} is the ambient air temperature measured inside the solar furnace.

No correction was applied for potential heat losses or duct heating between the receiver outlet and the heat exchanger.

The instantaneous thermal efficiency of the absorber, η_{th} , was then calculated with equation (7):

$$\eta_{th} = \frac{Q_a}{P_{solar,incident}} \quad (7)$$

The incident solar power ($P_{solar,incident}$) was determined from the flux distribution measured with a CCD camera (black-and-white image) calibrated against a Gardon radiometer.

The measurement was taken near the end of each test, under quasi-steady flux conditions, and the total power was obtained by integrating the calibrated flux map over the effective absorber aperture area. No cosine correction was applied, as the measurements were performed perpendicular to the incident beam.

3.1.4.4 Discussion of measurement limitations

The highly Gaussian solar flux distribution leads to strong spatial gradients at the absorber outlet. Using only three near-exit thermocouples (TK04–TK06, shown in Figure 9) introduces a sampling spatial bias in the estimation of the air outlet temperature: the sensors capture localized hot jets rather than the true area average outlet temperature. Consequently, a few operating points yielded apparent absolute efficiencies slightly above 100 %. This is not indicative of an energy-balance error, it reflects the temperature sampling limitation under a heterogeneous outlet field.

To ensure consistency and comparability across samples and operating conditions, results are reported as normalized efficiencies (η/η^*). This normalization preserves the relative performance trends while mitigating sensitivity to absolute-scaling artefacts caused by localized temperature sampling.

Planned mitigation and future work:

- Enhanced thermometry: add distributed/averaged temperature measurements (e.g., additional K-type grid, traversing probe, or multi-point rake) to better approximate the area-mean outlet temperature.
- CFD-assisted averaging: use high-fidelity CFD of the cup and outlet to compute measurement-to-area-mean correction factors for TK04–TK06 and validate them experimentally.
- Uncertainty treatment: propagate the outlet-temperature sampling error explicitly in the efficiency uncertainty budget and include sensitivity checks against the assumed outlet averaging method.

These actions will reduce the bias between localized and area-averaged temperatures and further improve the robustness of the thermal efficiency assessment.

3.1.4.5 Uncertainty evaluation

Uncertainty estimates for the main measured quantities were established as presented in the following Table 5:

Table 5: Summary of measurement uncertainties for the solar furnace experimental setup

Parameter	Instrument/Method	Uncertainty
Air and water thermocouples	Thermocouples	± 1.5 K (air) / ± 1.0 K (water)
Water mass flow rate	Flow meter	± 1.0 %
Solar flux (CCD + Gardon radiometer)	Flux map	± 3.0 %
Thermal efficiency	Propagated from above	± 3.0 - 5.0 %

Uncertainties were propagated by linear approximation. Although thermal losses between the receiver and the heat exchanger were neglected, they are expected to be small compared with the overall energy balance and will be assessed in future work.

3.1.4.6 Data management and traceability

All raw and processed data were stored in the PSA experimental database, together with metadata including sample ID, test date, shutter aperture value, measurement script version, and calibration files.

Data filtering and steady-state selection were applied consistently across all test series to ensure reproducibility.

3.2 IME Tower Test Loop (IME-CENER)

3.2.1 Description of the facility

In order to characterize thermal and structural performance of the OVAR working on real conditions, an experimental evaluation of one single absorber cup has been carried out at the solar tower facility at IMDEA Energy, Mostoles, Madrid (Spain). The targeted thermal power of the receiver module was from 30 up to 50 kWth with the aim of heating ambient air to high temperatures (800 – 900 °C).

A tailored transportable thermal loop for absorber module testing (see Figure 15) was used to test advanced ceramic foam modules at the IMDEA experimental tower (at larger scale than at the solar furnace). A simple scheme of the test loop is shown in Figure 12. The volumetric absorber module (1) is mounted at the inlet of the air duct/receiver pipe (2). The ambient air is forced through the experimental circuit by a blower (6). In particular, the air is forced through the absorber module (1), the receiver pipe (2), the air/water heat exchanger (4) and the flow meter (5). The absorber sample (1) will be irradiated by concentrated light of IME's heliostat field (see Figure 14). The heat exchanger and the receiver unit are insulated (3) in order to keep thermal losses negligible.

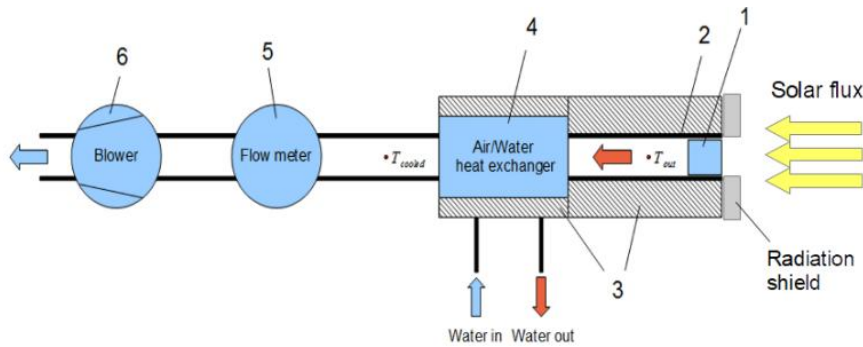


Figure 12. Test loop scheme

The air temperature is measured in a plane right after a following double membrane air mixer (3 K-type class 1 thermocouples in diagonal staggered configuration). The air mixer is of orifice type [3] and is needed in order to achieve a homogeneous mixing temperature of the air flow for correct representative air temperature measurement (see Figure 13).

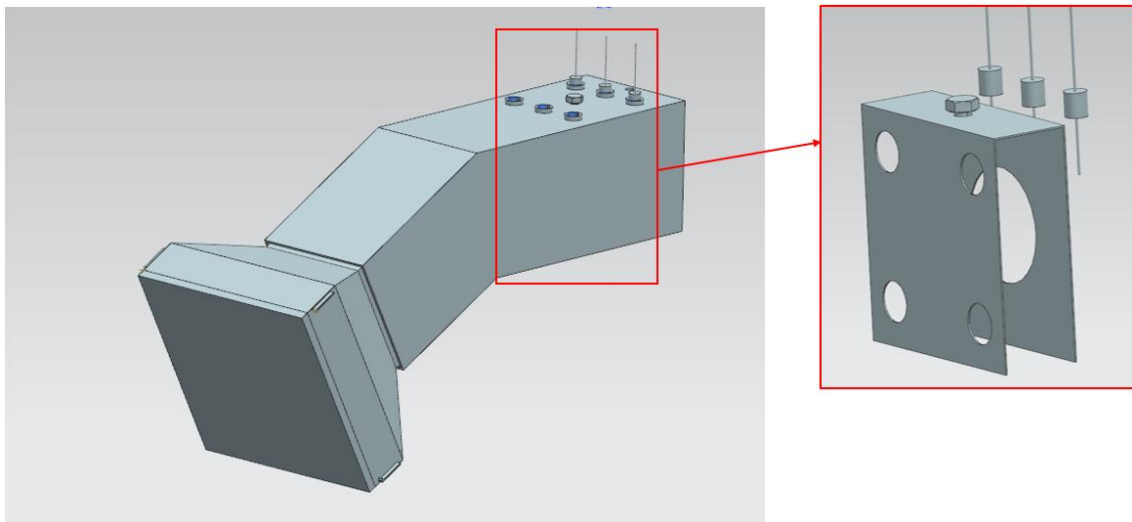


Figure 13. Air Mixer and thermocouple distribution after receiver

The air temperature is also measured at the heat exchanger exit (cold end) with a single K-type class 1 thermocouple. The air/water heat exchanger is a simple shell and tube design, having the water flow on the shell side and the air flow on the tube side. To allow high receiver operating temperatures, the receiver air duct is not welded to the heat exchanger shell, in fact it is only attached in loose manner with one single bolt at the top centre, such that the connection is statically determined and the inlet air duct can expand freely according to its temperature. Thus, no thermal stress is caused at the inlet section of the heat exchanger shell due to thermal expansion of the hot inlet duct. Both, the heat exchanger outer shell and the receiver inlet air duct are thermally insulated externally with layers of micro porous high-performance insulation material [4]. Thermal losses to the ambient are therefore negligible.



Figure 14: Experimental tower at IMDEA in Madrid

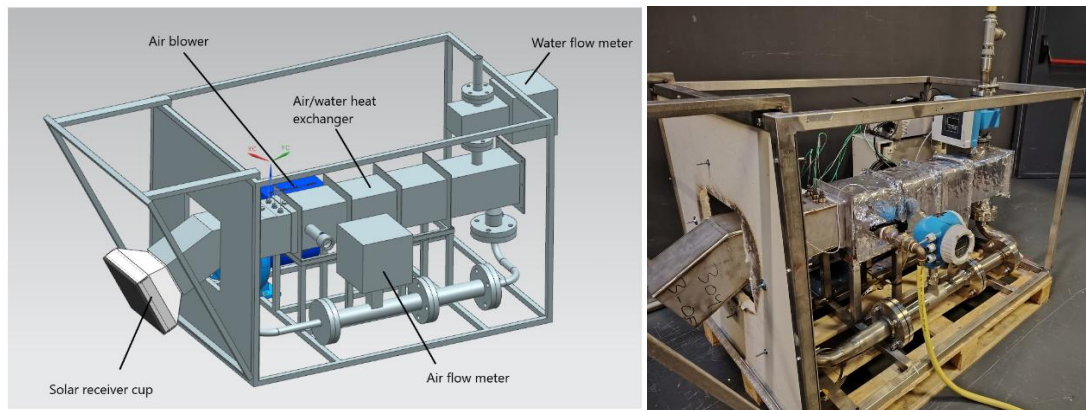


Figure 15: Transportable thermal test loop 30 kWth (800 x 1200 mm approx.); Receiver duct not yet insulated; 3D-model (a); Mounted test loop at CENER laboratory (b)

The air and cooling water mass flow are measured with a hot wire type flow meter and an electromagnetic flow meter, respectively (see Figure 16). The accuracy of the hot wire air flow meter is approximately 1% of measured value. The accuracy of the electromagnetic water flow meter is approximately 0.2% of measured value.



Figure 16: Hot wire air flow meter E+H model t-mass F 300 (a); Electromagnetic water flow meter E+H Promag W 400 (b)

Absorber module design

The module size for the experimental activity at IMDEA has been increased to 25 x 25 cm of aperture area. This gave valuable feedback regarding the performance of larger absorber tiles, when compared to the 14 x 14 cm tiles used in the CAPTURE project. The proposed cup design is shown in Figure 17.

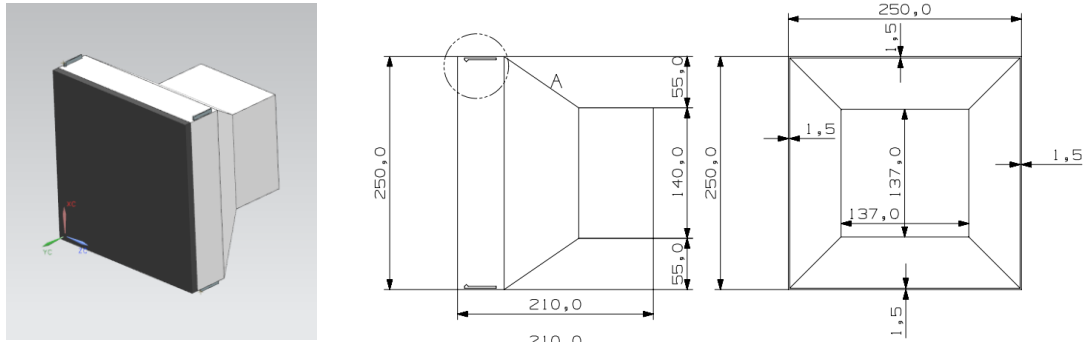


Figure 17: Absorber module design for testing at IMDEA

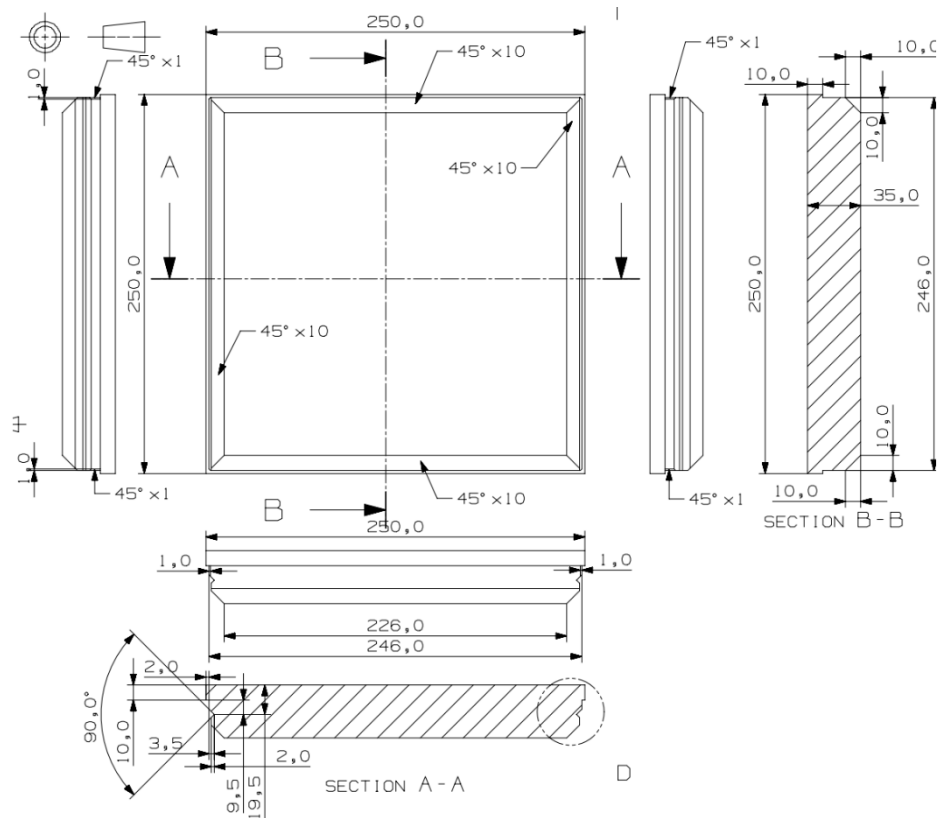


Figure 18: Absorber foam design for testing at IMDEA

For further information related to test rigs, please refer to D1.1 “Prototype Specifications”.

Figure 19 shows some detailed pictures of the absorber foam and receiver cup assembled using rails to support the foam.



Figure 19: Absorber module detailed pictures

A new thermal shield has been designed and made to couple the absorber module with the existing aperture in the IMDEA tower. Together with this shield, a structure has been manufactured that can place the skid with the air loop in the optimal position for the receiver to be exposed to radiation from the solar field. (see Figure 20).



Figure 20. a) Pyramidal thermal shield and b) structure for skid positioning

3.2.2 Testing Methodology

The receiver characterization was performed following the methodology used in Ref. [5] based on previous references such as [6, 7] in which the thermal efficiency of volumetric receivers formed by metallic meshes was estimated. This characterization is based on the analysis of the absorber performance; this method assumes that the power absorbed in the solar receiver by the air is the sum of the power at the receiver output plus the receiver losses. To carry out this method, first the temperature at the exchanger inlet/receiver outlet must be estimated at steady state, then the thermal power absorbed by air through the receiver and, from the radiant power, the receiver efficiency can be calculated.

Steady-state conditions were defined based on the stability of the air outlet temperature in the heat exchanger. Each test was considered stationary when this temperature remains constant or almost constant for a sufficiently long period (5 minutes). During each test instantaneous values were acquired every second to calculate the arithmetic means at the end of each trial, with the aim of obtaining reliable values.

Receiver efficiency is defined as the ratio between the output power of the air and the incident radiation on the receiver surface, i.e. the result of dividing of the heat absorbed by the air flowing through the receiver divided by the radiation on the front surface. This thermal efficiency depends mainly on the incident radiation on the receiver and the air flow through it (i.e. the receiver operating temperature). During this test campaign, thermal efficiency will be evaluated for different mass flow rates and incident radiation rates.

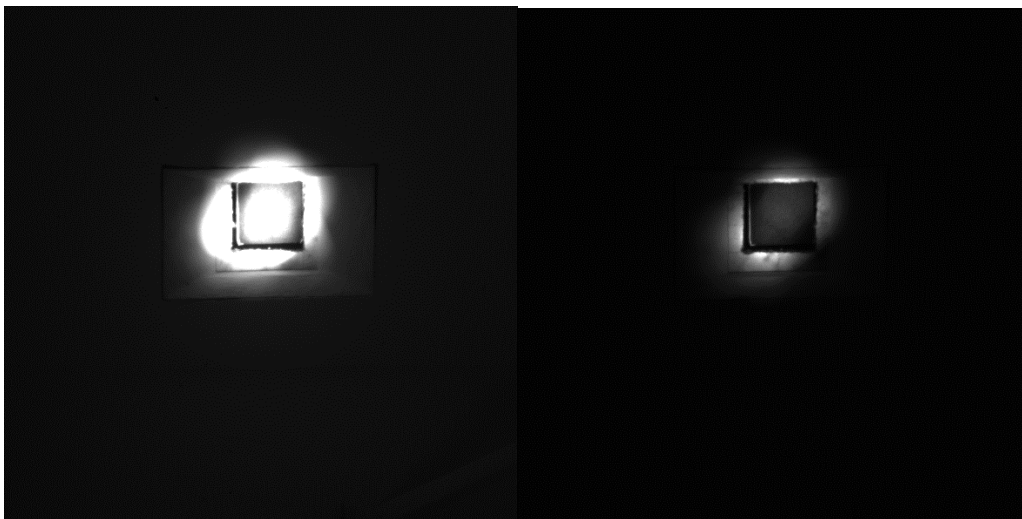


Figure 21. CCD pictures of the receiver in IME's tower

Figure 21 shows the incident radiation on frontal surface of the receiver measured in IME's solar tower with a CCD camera. With this map, the incident power at the receiver aperture can be calculated from the integration over the receiver surface (25x25 cm) following the eq. (8):

$$\dot{Q}_{rad} = \int_{-x}^x \int_{-y}^y q_{rad}(x,y) dx dy \quad (8)$$

Due to lack of homogeneity in the air outlet temperature, measurements made by type K thermocouples in this area (TK-01-TK03) are not reliable enough as well as to provide accurate power balances. For this reason, homogeneous air temperature outlet has been calculated by the power balance in the heat exchanger, as has been mentioned before. In order to calculate the heat absorbed through the receiver by the air, it will be necessary to know the thermal power absorbed by the water in the heat exchanger, estimate the losses in the heat exchanger, estimate the air temperature at the inlet of the heat exchanger/outlet of the receiver and estimate the losses of the receiver walls with the environment. Thermal losses in both the exchanger and the receiver were estimated from the K-type thermocouples placed on these surfaces. The temperature measurements of these thermocouples, with values equal or very close to the ambient temperature, allow us to affirm that the ceramic insulation used is enough to consider these losses negligible. The absorbed heat by the water in the heat exchanger as well as the air temperature at the receiver outlet/exchanger inlet were estimated from power balances. Power gained in the heat exchanger was calculated by the integration of the energy balance knowing the water temperatures at the inlet and at the outlet and the water mass flow through the heat exchanger, as shown in eq. (9).

$$\dot{Q}_W = \int_{T_{win}}^{T_{wout}} \dot{m} \cdot A \cdot c_{pW} \cdot (T_W) dT \quad (9)$$

Since the losses on the exchanger are negligible, as previously mentioned, the heat delivered by the air in the exchanger is equal to the power absorbed by the water. Consequently, applying the same balance to the air side of the exchanger, with the mass flow rate and Cp of the air and the measured heat exchanger air outlet temperature, the air temperature at the inlet heat exchanger can be estimated, following eq. (10) and eq. (11).

$$\dot{Q}_W = \dot{Q}_{air} \quad (10)$$

$$\dot{Q}_{air} = \int_{T_{airin}}^{T_{airout}} \dot{m} \cdot A \cdot c_{pair} \cdot (T_{air}) dT \quad (11)$$

Once the air temperature at the receiver outlet has been estimated, by means of a power balance and knowing the temperature at the receiver inlet which has been measured by the ambient temperature sensor placed near the inlet, it is easy to calculate the power absorbed by the air through the receiver, as shown in eq. (12).

$$\dot{Q}_{air_receiver} = \int_{T_{airin(ambient)}}^{T_{airout}} \dot{m} \cdot A \cdot c_{pair} \cdot (T_{air}) dT \quad (12)$$

With the solutions of eq. (8) and eq. (12) it is possible to estimate the thermal efficiency of the receiver by using eq. (13):

$$\eta_{th} = \frac{\dot{Q}_{air_receiver}}{\dot{Q}_{rad}} \quad (13)$$

3.2.3 Sensors and methodology used for the evaluation of the results

The instrumentation system used during the mid-scale test campaign is shown in Figure 22. It was designed to monitor the temperatures and air and water flows, needed to carry out power balances.

The system includes the following components:

- 1) 5 Type K thermocouples (TK01-TK06): TK01-TK03 are placed after air mixer (as is shown in Figure 13) and measure air temperature at the receiver outlet. TK-04 is placed in the air duct after the heat exchanger to measure air temperature needed for the power balance in this component. TK-05 and TK-06 are out of the loop and measure, in the first case, the temperature in the outer surface of the insulation to verify the adiabatic operation of the equipment and in the second case, the temperature of the ambient air which enters the thermal loop.
- 2) 2 4-Wire PT100 (PT101-PT102): As the ΔT in the water side of the heat exchanger is much lower (two orders of magnitude) than in the air side, temperature gauges in the water side must be much more accurate. For that, 4 Wire PT100 are selected to measure water temperature instead of Type K thermocouples.
- 3) A hot wire air flow meter (FM01): The air flow rate was measured with a hot wire flowmeter (model Endress+Hauser t-mass F300 DN50) rated for operation up to 180°C and 520 kg/min nominal capacity.
- 4) An electromagnetic water flow meter (FM02): The water flow rate was measured with an electromagnetic flowmeter (model Endress+Hauser Proline Promag W400 DN25) rated for operation up to 80°C and 2.4 l/s nominal capacity.
- 5) Blower control (BC01): The main air blower supplied ambient air to the loop. Its rotational speed was adjusted, using a frequency converter, to reach the desired flow rate in each test.

All sensors were connected to a multi-channel data acquisition system operating at 1 Hz sampling frequency. Each channel was calibrated and logged continuously during tests. Data were post-processed using in-house scripts to compute instantaneous and averaged values of temperature and flow.

The estimated measurement uncertainties were: ± 0.15 K for Type K thermocouples, 0.03 K for 4-W PT100, 1% for air flow meter and 0.2% for water flow meter.

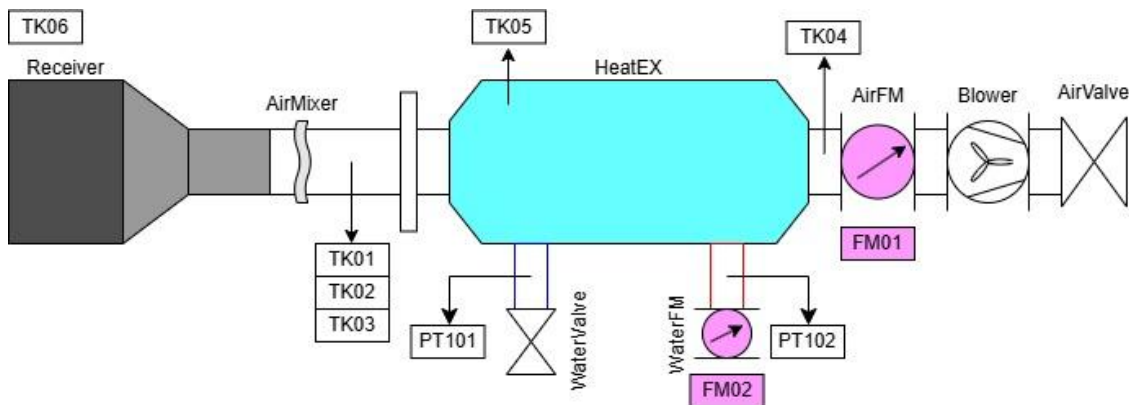


Figure 22. Schematic of portable air loop for solar receiver testing used at IMDEA Energy

4 Results

4.1 Solar Furnace Campaign (Task 6.1 – CIEMAT-PSA)

4.1.1 Test matrix and operating conditions

The experimental campaign conducted at the CIEMAT-PSA solar furnace was structured into three main types of tests, each addressing a specific objective of the small-scale absorber evaluation:

- Cold flow tests to assess aerodynamic behaviour,
- Thermal performance tests to evaluate efficiency and stability under solar irradiation, and
- Optical properties evaluation to examine changes in optical parameters before and after thermal exposure.

Table 6: Summary of the test matrix and main operating conditions for the solar furnace campaign (Task 6.1 – CIEMAT-PSA)

Test type	Goal	Configuration of the absorber	Operational parameters	Measured variables
Cold flow tests	Evaluate fluid flow behaviour	Empty cup (without absorber) with 3 outlet geometries: • 60 mm orifice • 40 mm orifice • 30 mm orifice	• No solar flux • Ambient temperature • Blower speed: 25%, 50%, 75%, 100%	• Air mass flow rate
Thermal performance tests	Determine thermal efficiency	Cup with absorber (9 samples) Single outlet of 60 mm	• Solar flux levels: ~5, ~7.5, ~10 kW_{th} • Mean air outlet temperature: 600, 700, 800°C • Maximum solar flux: 1 MW/m²	• Air inlet and outlet temperatures • Air mass flow • Water inlet/outlet temperatures • Water flow • Incident solar flux
Optical properties evaluation	Assess optical evaluation due to oxidation and thermal cycling	Absorber samples before and after solar tests	• Room temperature optical characterization	• Spectral absorptance • Hemispherical emittance

4.1.1.1 Cold Flow Tests

The cold flow tests were performed without solar irradiation, using an absorber cup without any absorber material. The objective of these tests was to quantify the aerodynamic resistance of the cup under different outlet configurations and airflow rates.

Three outlet geometries were tested:

- $\varnothing_{\text{outlet}} = 60 \text{ mm}$
- $\varnothing_{\text{outlet}} = 40 \text{ mm}$
- $\varnothing_{\text{outlet}} = 30 \text{ mm}$

For each configuration, the blower rotational speed was adjusted to obtain four airflow conditions, corresponding to 25%, 50%, 75%, and 100% of the nominal blower capacity.

The resulting dataset allowed determination of the air flow variation across the absorber geometry,

providing a reference for the subsequent thermal tests.

4.1.1.2 Thermal Performance Tests

Following the aerodynamic characterization, the absorber modules were tested under concentrated solar flux to evaluate their thermal performance, efficiency, and operational stability under relevant operating conditions.

Preliminary experiments indicated that certain absorber materials were prone to oxidation under very high flux densities. Therefore, the maximum incident flux during testing was limited to approximately 1 MW/m^2 , while the target air outlet temperature was initially set between 800°C and 900°C . To further mitigate oxidation risks, the maximum operating temperature was subsequently restricted at $\sim 800^\circ\text{C}$.

Each absorber sample was tested under three nominal solar power levels, approximately 5, 7.5, and $10 \text{ kW}_{\text{th}}$, combined with the three temperature levels (600°C , 700°C , and 800°C) resulting in nine operating points per absorber. The incident solar power was regulated by controlling the shutter aperture of the solar furnace.

Because the solar flux distribution on the absorber surface was highly non-uniform (Gaussian profile), it was difficult to obtain a representative air outlet temperature. Instead of relying on internal thermocouples (TK15–TK17 in Figure 9) with uncertain positioning, the mean temperature of the near-exit thermocouples (TK04–TK06 in Figure 9), located in the same plane downstream of the absorber, was used to estimate the average hot air temperature at the receiver outlet. The ambient temperature, measured within the solar furnace facility, was used as the inlet temperature reference.

During the data evaluation, it was observed that the direct measurement of the air mass flow rate did not produce consistent energy balances between the air and water sides. Therefore, the air flow rate was recalculated indirectly using a calorimetric balance with the air–water heat exchanger, under the assumption that all the thermal power gained by the air in the receiver was transferred to the water. This approach provided a more consistent estimation of the thermal power absorbed by the air.

For each steady-state condition, the thermal efficiency of the absorber was calculated as the ratio between the useful thermal power transferred to the air and the total incident solar power on the aperture.

The solar power was determined from the CCD flux images calibrated with a Gardon radiometer, captured near the end of each test under quasi-steady conditions.

Due to the localized temperature measurement and the non-uniform flux profile, small deviations occasionally led to calculated efficiencies slightly above 100 %. These values were retained in the dataset but interpreted as the result of local temperature oversampling, rather than as physically valid efficiencies.

Further work, including detailed CFD simulations and additional distributed temperature measurements, is planned to refine the temperature averaging method and improve the accuracy of the thermal efficiency determination.

4.1.1.3 Optical Properties Evaluation

Complementary tests were carried out to assess the optical characteristics of the absorber samples before and after exposure to solar irradiation. The main parameters of interest were the spectral absorptance and hemispherical emittance, which are indicative of surface degradation and oxidation effects at high temperature.

These measurements aimed to identify potential changes in optical behaviour resulting from the thermal cycles applied during the solar tests.

This three-step experimental matrix provided a consistent framework for evaluating the small-scale absorber modules under representative thermal and radiative conditions, enabling cross-comparison of aerodynamic, thermal, and optical performance prior to validation at larger scales.

4.1.2 Performance results

4.1.2.1 Cold Flow Tests

The cold flow tests were conducted to assess the aerodynamic behaviour of the absorber cup for different outlet diameters in the absence of solar irradiation. The objective of this preliminary study was to determine the influence of the outlet orifice on the air mass flow rate driven by the blower.

Three outlet configurations were tested, 30 mm, 40 mm, and 60 mm, while the blower rotational speed was varied between 25%, 50%, 75% and 100% of its nominal capacity.

Figure 23 shows the normalized air mass flow rate as a function of the blower speed for the three outlet diameters. Each data series was normalized with respect to the maximum measured flow rate (corresponding to the 60 mm outlet at 100 % blower speed), allowing a direct comparison of relative flow behaviour.

A clear correlation is observed between the outlet diameter and the attainable mass flow rate. As expected, larger outlet openings produce higher flow rates due to reduced aerodynamic resistance, whereas the smaller diameters (30–40 mm) exhibit a stronger dependence on blower speed.

At 100 % blower capacity, the air mass flow for the 30 mm outlet reaches approximately 70 % of the reference case (60 mm), while the 40 mm outlet achieves about 90 % of the reference flow.

The relationship between blower speed and flow rate is approximately linear within the tested range, indicating stable and predictable blower operation. However, at low blower settings (25 and 50 %), the influence of the outlet orifice becomes more pronounced, suggesting that the smaller openings impose additional losses that limit flow acceleration.

Based on these results, the 60 mm outlet configuration was selected for the subsequent thermal performance tests, as it provided an adequate compromise between flow uniformity, pressure drop, and mechanical stability of the absorber cup.

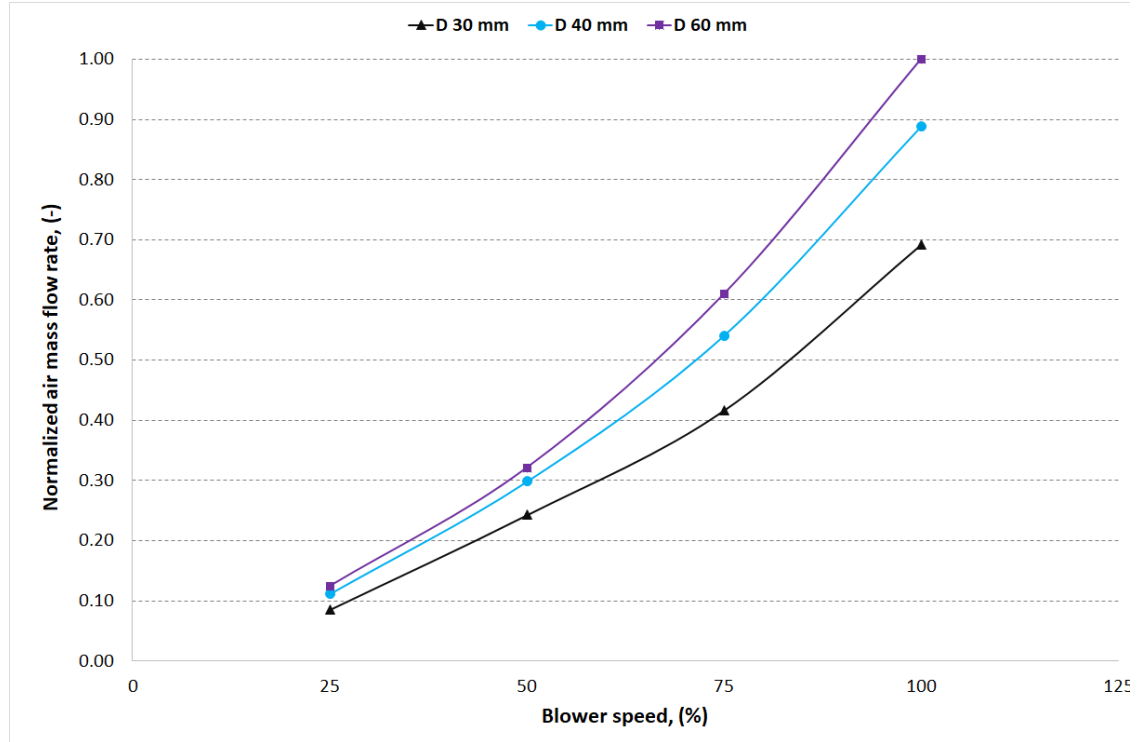


Figure 23: Normalized air mass flow rate versus blower speed for different outlet diameters

4.1.2.2 Thermal Performance Tests

The thermal tests were analysed for nine absorber samples over nine operating conditions (three solar power levels: ~ 5 , ~ 7.5 , ~ 10 kW_{th}; and three nominal mean outlet-temperature levels: 600, 700, 800 °C). For each test, steady-state windows were identified, and the averaged values were extracted for the useful power gain (water calorimetry), near-exit air temperatures (TK04–TK06), air mass flow (indirect measurement obtained via heat balance), incident flux/power (CCD + Gardon radiometer) and thermal efficiency. Results are reported in normalized form and absorbers are named following Table 3. Uncertainty of the measurements correspond to the propagated measurement uncertainty ($\approx \pm 3\text{--}5\%$, see Section 3.1.4).

To illustrate representative behaviours, the following results are presented:

- (i) Normalized power gain versus relative air flow for two representative absorbers;
- (ii) Normalized thermal efficiency versus relative air flow for the nine absorbers; and
- (iii) Performance ranking with three parameter encompassing evaluation methods versus air outlet temperature for all nine absorbers

1) Representative normalized power gain trends

Figure 24 shows normalized power gain ($P/P_{\max}$, from water calorimetry) as a function of normalized air mass flow ($\dot{m}/\dot{m}_{\max}$) for two representative absorbers (R1-169 and R2-6 from Table 3) at three incident power levels (~ 5 , 7.5 and 10 kW_{th}). As expected, useful heat increases with both the incident power and the flow rate. Scatter symbols are 30–60 s steady-state averages.

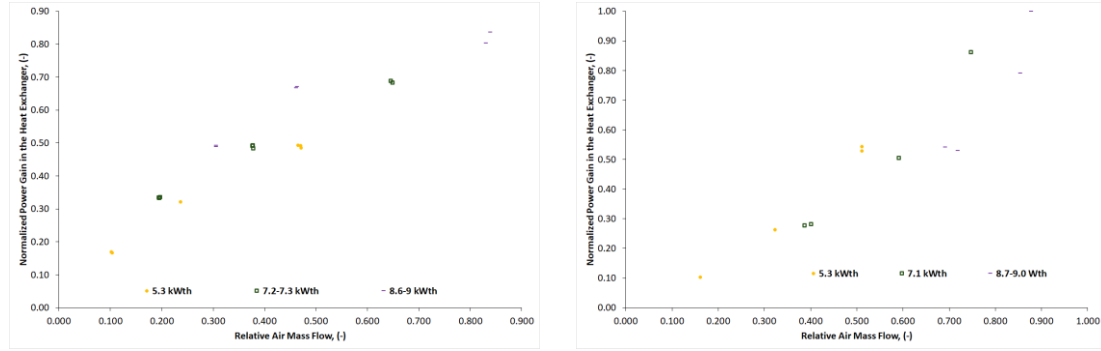
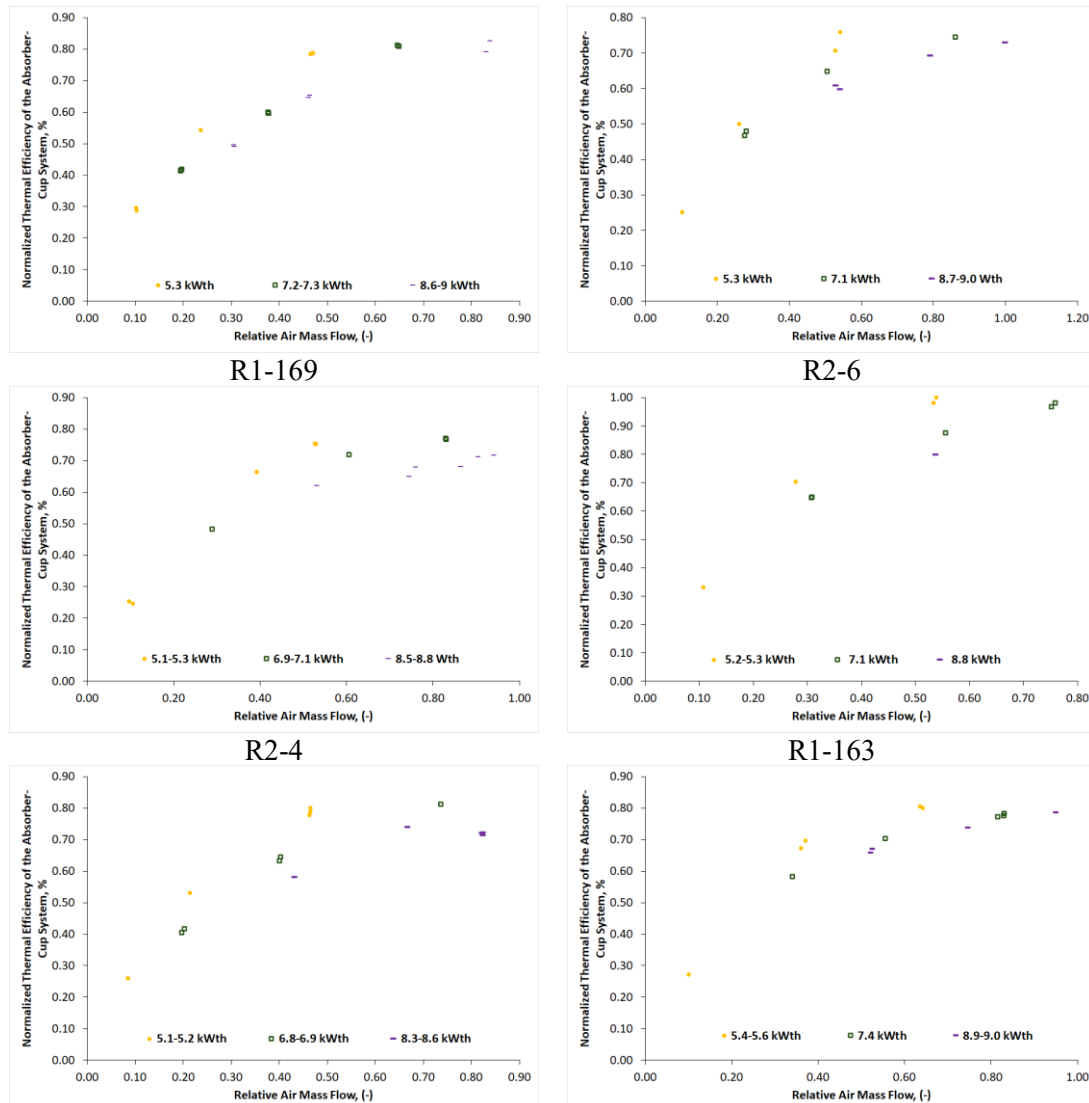


Figure 24: Normalized power gain (from water-side calorimetry) versus normalized air mass flow for at three incident power levels (~5, 7.5, 9 kW). R1-169 (left). R2-6 (right).

2) Normalized thermal efficiency trends

Figure 25 compares the normalized thermal efficiency (η/η^*) against normalized air mass flow ($\dot{m}/\dot{m}_{max}$) for the nine absorbers at three representative incident power levels (~5, 7.5 and 10 kW_{th}). Here, η^* denotes the highest efficiency measured among all absorbers. This representation enables a fair comparison, where scatter symbols derive from the 30–60 s steady-state averages.



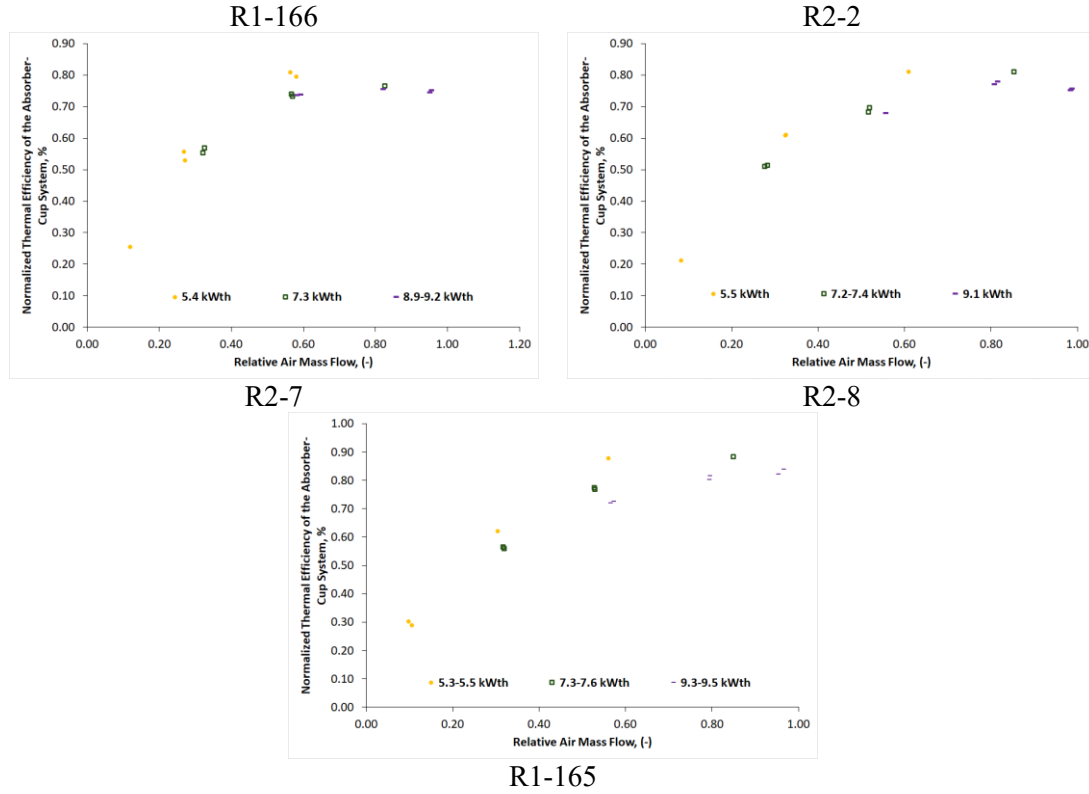


Figure 25: Normalized thermal efficiency (η/η^*) versus normalized air mass flow ($\dot{m}/\dot{m}_{max}$) for the nine absorbers at three incident power levels (~5, 7.5 and 10 kW_{th})

Across the full campaign, three consistent observations emerge:

- (i) Normalized thermal efficiency increases with power and flow, then shows diminishing returns: At fixed temperature, η typically increases from ~5 to 7.5 kW_{th} and then exhibits diminishing increments approaching 9–10 kW_{th}, consistent with local heat-transfer limits under the outlet-temperature cap.
- (ii) Sensitivity to outlet temperature: At fixed incident power, increasing the nominal outlet temperature (air mass flow decrease to increase temperature from 600 to 800 °C) generally reduces η , due to higher thermal losses from the imposed maximum outlet temperature.
- (iii) Separation between absorber families: A stable separation appears between top-tier candidates, a mid-tier, and lower performers. Top-tier samples maintain high η/η^* over a broad flow range; lower performers show larger variability and earlier saturation.

3) Performance ranking

To obtain a robust and transparent ranking, three complementary analyses to the normalized efficiency data (η/η^*) were applied:

- (i) Method 1 – Temperature-range comparison: Data were grouped into operational temperature ranges (tertiles of the full and precise temperature dataset). For each absorber

and power level (shutter aperture), the mean of η/η^* and its standard deviation were calculated. Within each temperature range, absorbers were ranked from highest to lowest. This method is a physically consistent comparison without assuming a functional dependence between η and temperature.

- (ii) Method 2 – Temperature normalized efficiency: A global linear model $\eta = a + b \cdot T$ was fitted to quantify the average temperature dependence (b) of each absorber and flux condition. Each measurement was then normalized to a reference temperature ($T_{ref} \approx 700$ °C):

$$\eta_{norm} = \eta + b \cdot (T_{ref} - T) \quad (8)$$

This yields comparable efficiency values at the same reference temperature across all absorbers and power levels. Ranking was produced from the mean η_{norm} per absorber and power level.

- (iii) Method 3 – Multivariable regression (temperature, power, absorber): A linear model $\eta_{norm,(iii)} = a + b_1 \cdot T + b_2 \cdot P + \sum_i (c_i \cdot Absorber_i)$ was fitted, isolating the effects of temperature (T), incident power (P) and absorber (c_i). Expected efficiencies were then evaluated under reference conditions ($T = 695$ °C, $P = 7$ kW) to produce an adjusted ranking that reflects relative performance under equivalent operation.

All three approaches produce consistent hierarchies with only minor permutations in the mid-tier. The top two positions are invariant across methods, while differences between Methods 1–3 mainly affect positions #3 to #6, reflecting the stricter corrections for temperature and power in Methods 2–3.

Table 7: Summary of absorber ranking according to the three methods (from highest to lowest)

Ranking	Method 1	Method 2	Method 3
#1	R1_163	R1_163	R1_163
#2	R1_165	R1_165	R1_165
#3	R2_8	R2_2	R2_2
#4	R2_2	R2_8	R2_8
#5	R2_7	R2_7	R1_169
#6	R1_169	R1_169	R2_7
#7	R1_166	R2_6	R2_6
#8	R2_4	R1_166	R1_166
#9	R2_6	R2_4	R2_4

It is observed that:

- R1_163 and R1_165 consistently occupy #1–#2, confirming their robust performance across temperature and power levels.
- The upper mid-tier alternates between R2_2 and R2_8 depending on whether temperature and power corrections are applied explicitly (Methods 2–3).
- R1_169 and R2_7 cluster in the middle positions, with modest sensitivity to the chosen method.
- R2_6, R1_166, and R2_4 populate the lower ranks in most cases.

Overall, the combined analysis indicates that several absorber designs deliver high and stable normalized efficiency under relevant operating conditions. The concordance of the three ranking

methods strengthens confidence in the list of top candidates for upscaling and long-term validation. Remaining discrepancies are attributable to outlet-temperature sampling under non-uniform flux and will be addressed using CFD-assisted averaging and enhanced thermometry, as outlined in Section 3.1.4.4.

4.1.2.3 Optical Characterization Tests

Taking advantage of the available facilities at PSA, additional spectral and hemispherical measurements were carried out to determine the initial optical properties of the absorber and to evaluate their stability after thermal cycling. This activity provides valuable information on potential oxidation, discoloration, or other surface effects induced by repeated exposure to concentrated solar radiation.

The optical properties were characterized at PSA using the instruments described in section 3.1.3.2. Measurements were performed at room temperature (25 °C), and the emittance was additionally evaluated at 600, 700, and 800 °C using Planck-weighted integration. Each absorber sample was analyzed before and after solar and thermal cycling tests. Due to intermittent availability of liquid nitrogen, some post-test emittance measurements could not be performed but will be completed in future updates.

The results of absorptance ($\alpha_{s,h}$) and emittance (ϵ_{th}) measurements are summarized in Table 8.

Table 8: Summary of optical properties before and after thermal cycling

Absorber	$\alpha_{s,h,in}$	$\alpha_{s,h,out}$	$\Delta\alpha$	$\epsilon_{th,in,800^\circ C}$	$\epsilon_{th,out,800^\circ C}$	$\Delta\epsilon$	Observation
R1-163	0.951	0.950	-0.001	0.942	0.946	0.004	Stable
R1-165	0.968	0.97	0.002	0.961	0.957	-0.004	Stable
R1-166	0.962	0.965	0.003	0.956	—	—	Not measured
R1-169	0.964	0.965	0.001	0.942	—	—	Not measured
R2-2	0.968	0.969	0.001	0.958	—	—	Not measured
R2-4	0.970	0.971	0.001	0.961	—	—	Not measured
R2-6	0.967	0.969	0.002	0.956	—	—	Not measured
R2-7	0.968	0.968	0.000	0.949	0.955	0.006	Stable
R2-8	0.967	0.941	-0.026	0.957	0.951	-0.006	Slight degradation

The initial hemispherical absorptance values range between 0.95 and 0.97, confirming the high optical quality of all absorbers. After thermal cycling, absorptance remains stable for most samples ($\Delta\alpha \leq \pm 0.005$), with only one case (R2-8) showing a small decrease (~ 0.03), possibly related to localized surface oxidation.

Thermal emittance values at 800 °C lie in the range 0.94–0.96, with variations smaller than ± 0.01 after cycling. These results indicate very limited degradation and confirm the good optical durability of the absorber materials.

Overall, the optical results confirm that the absorber maintain their solar absorptance and thermal emittance after multiple solar exposure cycles. The minimal changes observed in both properties demonstrate the optical and thermal stability of the investigated materials.

These findings reinforce the conclusion that the absorber concepts developed within ASTERIX-CAESAR exhibit robust optical durability and are well suited for long-term operation in high-temperature solar receivers.

4.2 Tower Campaign (Task 6.2 – IME)

The experimental campaign conducted at the IMDEA Energy solar tower was structured with the main objective of testing the volumetric receiver under real radiative conditions and validating this design at larger absorber tile size (25 x 25 cm) prior to its installation in the CIEMAT-PSA prototype. The test campaign will be conducted with the aim of reproducing the receiver's nominal operating conditions. To this end, during the experiments both the number of heliostats directed at the receiver aperture and the air mass flow rate through the receiver will be varied in order to obtain a complete characterization. The objective is to demonstrate the continuous and stable operation of the receiver while achieving an outlet air temperature of 800 °C. Air mass flow during tests were limited by the characteristic curve of the blower, which can provide an air flow between 22 and 137 kg/h. Therefore, to protect the equipment from overheating, the test campaign will begin by operating the receiver at the minimum air mass flow rate, thereby achieving the target temperature of 800 °C with the lowest possible incident radiation. Once this operating point is reached, both the number of heliostats and the air mass flow rate will be progressively increased until the receiver's nominal incident thermal power of 30 kWth is achieved.

Due to several delays as a result of civil works at IMDEA Energy installations and the necessary modifications and works on the tower to allow the installation of devices like the air loop described in section 3.2, the tests defined in the previous section have not been completed at the due date of the deliverable (31st of October 2025). However, the operation of all the equipment has been verified, including the air loop, the water loop, and the acquisition system, by testing the equipment with two heliostats, exposing the receiver to radiation (albeit low), and checking that all components are working correctly, as is shown in the following figures (Figure 26). Thus, the test facility was completely ready by October 2025 to carry out the test plan.

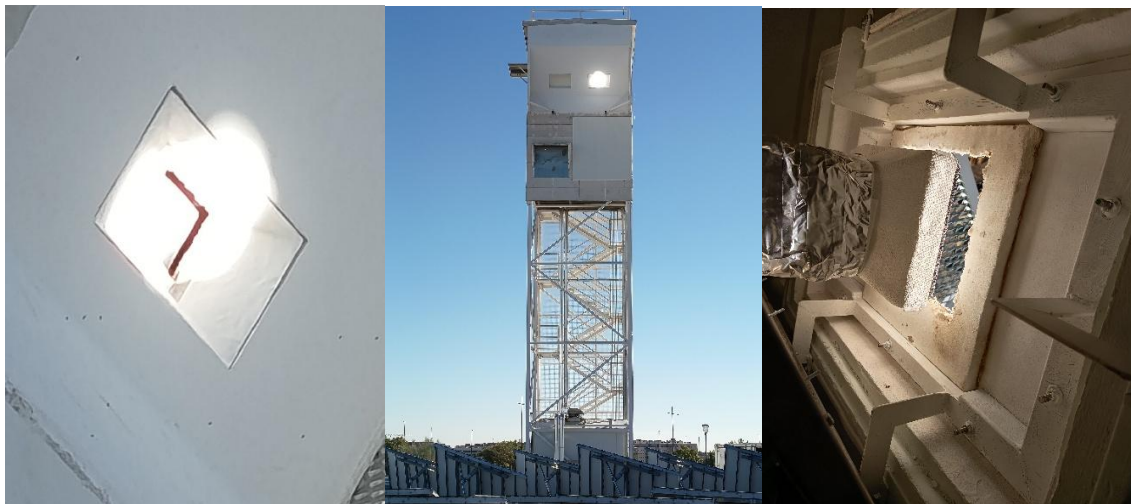


Figure 26: ASTERIX-CAESAR 25x25 cm receiver test with two heliostats

Due to additional delays caused by absorber foam manufacturing issues at the larger size of 25 x 25 cm, the testing could not start before February 2026. In February 2026, the first receiver tests were carried out at the tower facility. The initial prototype tested had the previously specified dimensions (25 × 25 cm) and showed, at first glance, some manufacturing defects in the form of sealed regions (see Figure 27) or areas with very low porosity, which could lead to inefficient heat transfer. These defects are related to the foam manufacturing methodology. In an effort to reduce the receiver manufacturing cost, IWKS tested new foam fabrication approaches that, up to that point, had not proven fully satisfactory, as they resulted in porosity defects, particularly in the central region of the foam. As a result, and being aware of the risk of overheating the receiver, the initial tests were conducted very cautiously following the previously described methodology, increasing the number of heliostats in increments of two in order to obtain a slow heating curve.

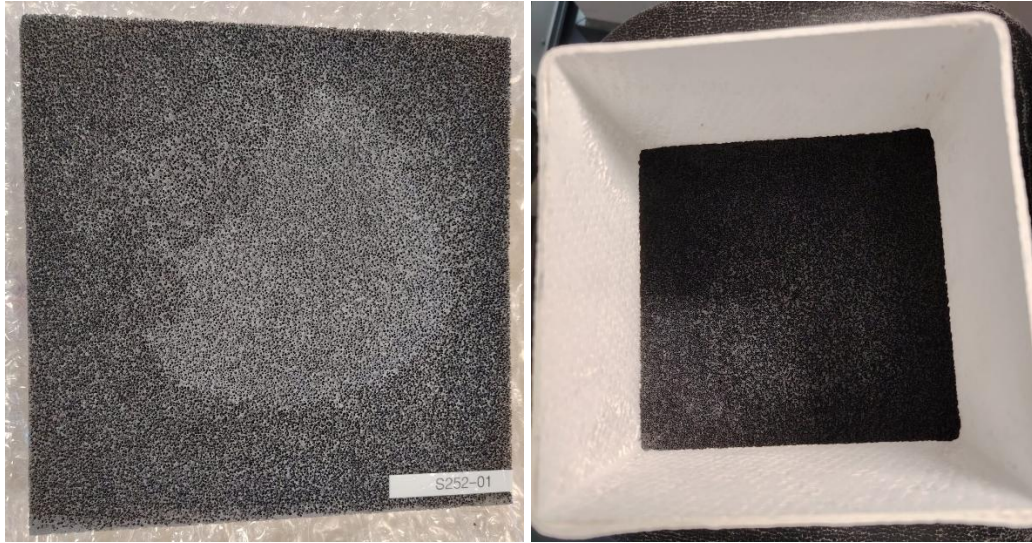


Figure 27: ASTERIX-CAESAR 25x25 cm receiver with low porosity

As a result, during the first day of testing, only an outlet air temperature of 650 °C was reached. The following figure (Figure 28) shows the flux at the receiver aperture during the test, for a DNI of 958 W/m² calculated from ray-tracing of the solar field, assuming a tracking error of 2 mrad and a mirror reflectance of 90.58%. This value was obtained by averaging 5 reflectometer measurements performed on one of the used heliostats on the test.

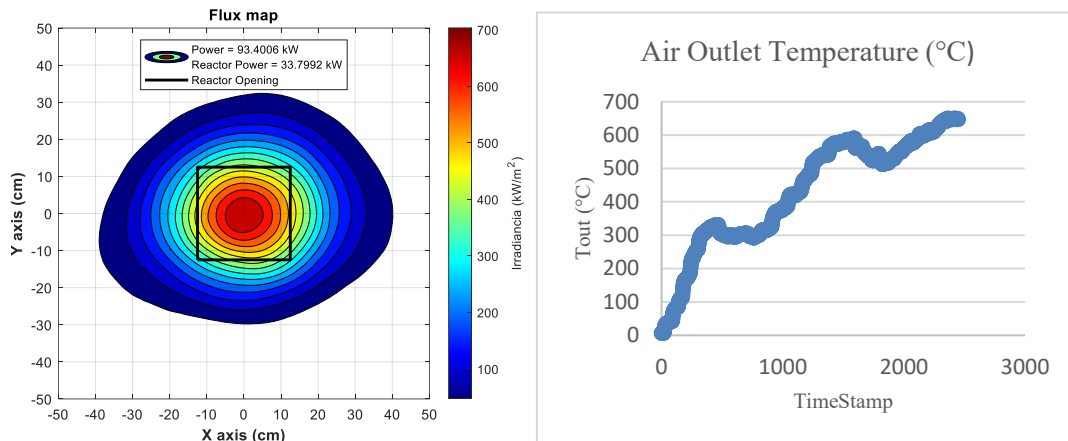


Figure 28: a) Flux map on receiver surface during first test b) Air outlet temperature during first test at IME tower

Despite having a reactor power of 33 kW, the measurements of air mass flow rate and temperature in the air loop indicated absorbed power values of approximately 15 kW, resulting in efficiencies significantly below the expected values, with maximum operating temperatures of 650 °C (the heating ramp is shown in Figure 28). During this first test, an unusual behaviour in the outlet air temperature was observed, as it did not increase beyond 650 °C despite the continued addition of heliostats. For this reason, the test was stopped.

After analysing the results, it was hypothesized that this low thermal performance could be attributed to these manufacturing defects. To verify this, during the second test an attempt was made to increase the operating temperature to reach the nominal target. The same procedure was followed, and in this case up to 60 kW were achieved at the receiver; however, the air temperature could not exceed 700 °C, with even lower efficiencies than on the previous day.

It must be noted that the air temperature was not measured right after the foam. The air

temperature thermocouples were placed at about 50 cm downstream the absorber because of the duct design with a bend that considers the inclination of the radiation shield (see Figure 13).

Figure 29 shows the peak flux map during this test, as well as the number of heliostats focused at this point (72).

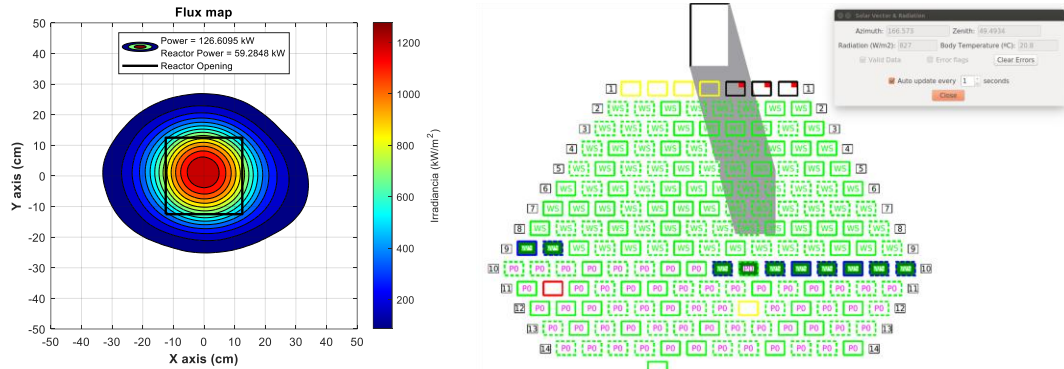


Figure 29: a) Flux Map on receiver surface during second test b) Number of heliostats focused

Unfortunately, before reaching the reference temperature at the thermocouples, smoke was observed in the air loop duct, together with visible oxidation in the CCD camera. The test was stopped to inspect the condition of the foam, which showed severe oxidation and even material detachment in the most thermally stressed regions. Figure 30 illustrates this degradation.

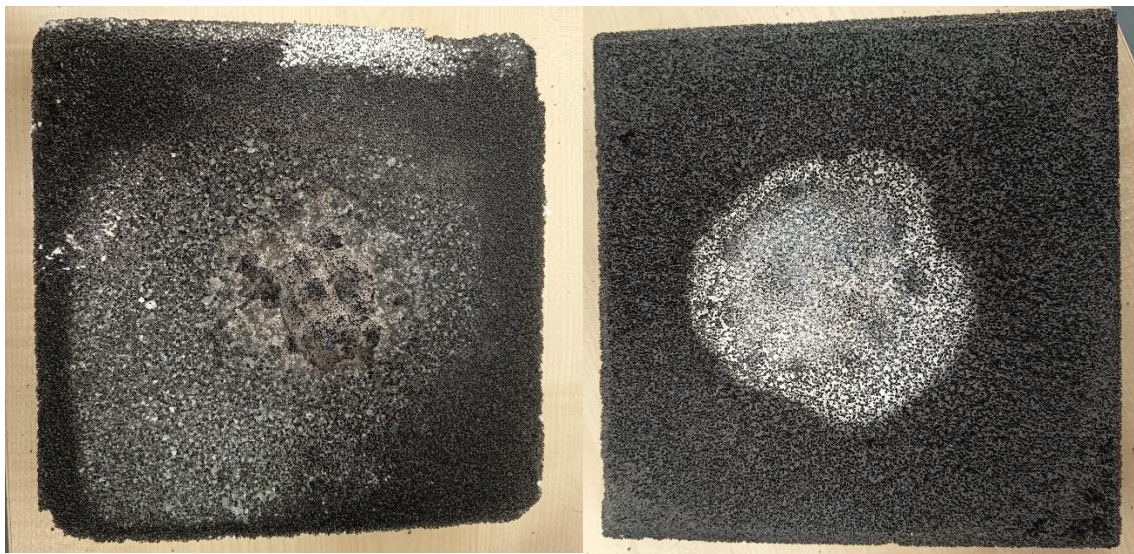


Figure 30: First Foam degradation on a) Frontal face and b) Rear face

As shown in the previous figure, the foam was rendered unusable after the second test, and it was therefore decided to manufacture a second version. For this second iteration, the size was changed to the final dimensions to be installed in the full prototype, increasing from 25x25 cm to 24.6x17.6 cm. The air loop was adapted to accommodate the new receiver. For this second foam version, the manufacturing methodology was adjusted in an attempt to mitigate the previously observed porosity issues. Although the visual appearance of the new foams was improved, the results were still not fully satisfactory.

For the tests with the new foam installed, the same experimental methodology described above was followed, gradually increasing the number of heliostats until the nominal operating temperature was reached. Despite the improvement in porosity, this foam was also unable to achieve the required temperature, exhibiting behavior similar to that of the first version. However, it was capable of reaching a maximum operating temperature of 750 °C (at the downstream

thermocouples), which is 100 °C higher than that achieved with the previous foam under comparable irradiation levels (Figure 31).

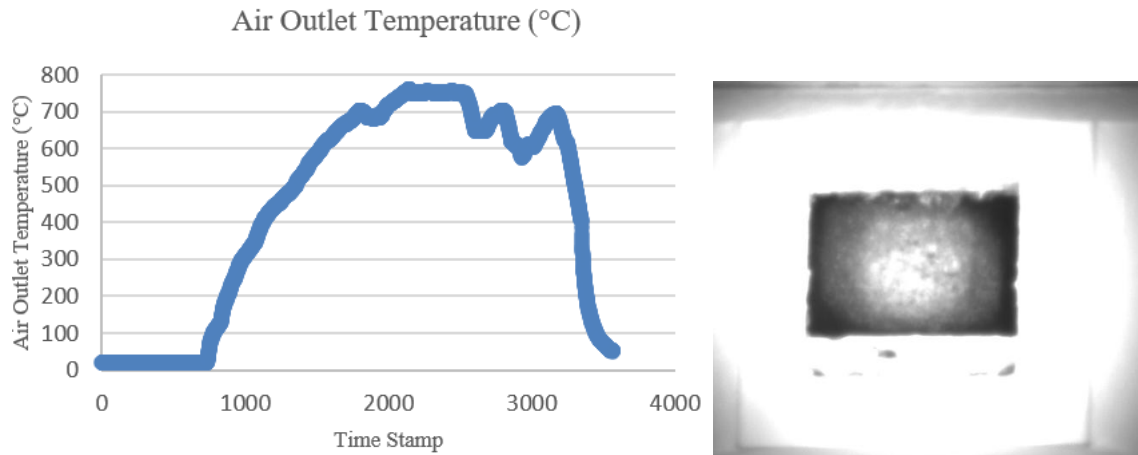


Figure 31: a) Air outlet temperature during second foam test at IME tower b) Oxidation observed in the CCD camera

Following the same testing procedure, the experiment was continued until signs of oxidation became visible in the CCD camera (Figure 31). The results obtained with this second foam are presented in Figure 32, a slight degradation of the cup is also visible, partially resulting from the heating of the thermal shield itself.

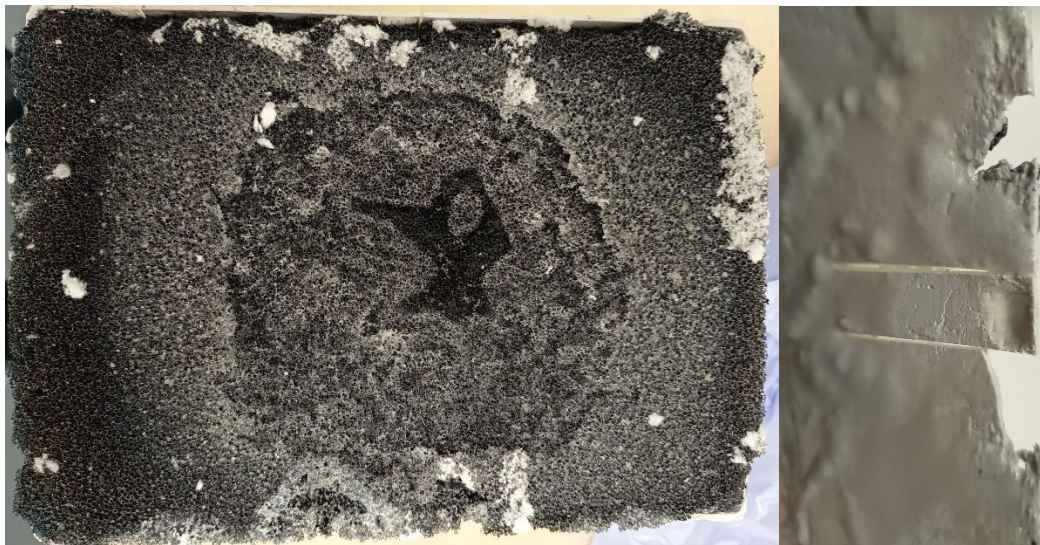


Figure 32: Second Foam degradation on frontal face and cup degradation on top side

A third foam version was tested using the same receiver configuration, but silicone infiltrated SiC¹, a simpler manufacturing methodology, with the aim of ensuring adequate air flow through the structure. Unfortunately, although this third version was able to reach the target temperature of 800 °C, this condition was sustained only for a very short period of time. The final outcome was similar to that observed with the two previous foam versions. Figure 33 shows the temperature profile recorded during the test, where the brief attainment of 800 °C can be observed at the end of the experiment, together with the final condition of the foam after testing. The foam exhibited clear signs of oxidation and degradation, confirming the limitations of the material under the tested operating conditions.

¹ Silicon Infiltrated Silicon Carbide (SiSiC) foam can be easier manufactured because of no shrinkage, but the oxidation resistance is lower.

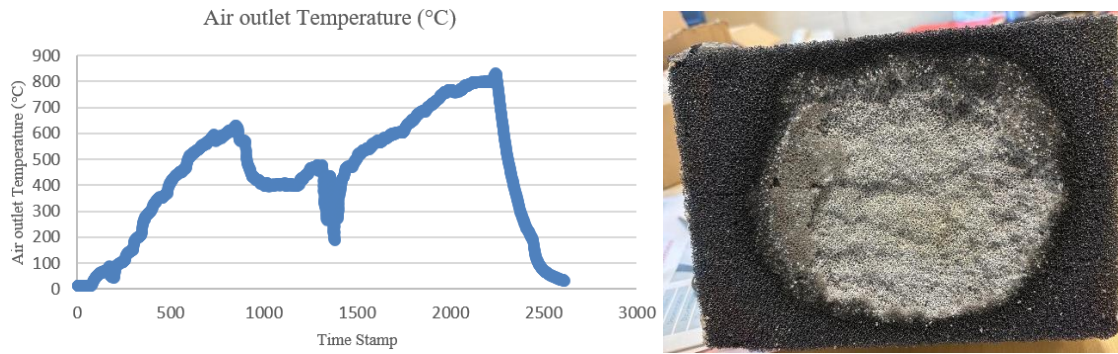


Figure 33: a) Air outlet temperature during second foam test at IME tower b) Third Foam degradation on frontal face

Since the severe oxidation levels observed in above figures must have happened at substantially higher temperatures than that observed in the downstream air duct, it was concluded that the temperature at the rear surface of the absorbers must be measured as well. Therefore, for the next experiments with improved foams, additional 3 k-type thermocouples (with 0.5 mm of diameter) were placed at the rear surface of the foam.

Following the analysis of the experimental data and the results obtained from the three unsuccessful receiver tests, it was concluded that the poor performance could not be attributed solely to the porosity defects. While these defects led to non-uniform cooling of the receiver, generating hot spots and causing local temperatures significantly higher than expected, an additional mechanism was identified.

Due to the highly concentrated nature of the incident radiation, which was focused into a relatively small spot, local overheating in the central region of the receiver may have accelerated the oxidation processes. This effect is believed to have generated a self-amplifying temperature increase in the central foam region. The air flowing through the central region of the receiver reaches significantly higher temperatures than the air near the edges, resulting in a local reduction in air density. Consequently, the mass flow rate through this region decreases, reducing the cooling capacity and leading to further temperature increases. This, in turn, promotes additional oxidation and degradation of the foam, further increasing the local temperature. The combination of these effects creates a self-reinforcing cycle that accelerates both the heating and oxidation of the receiver material.

To ensure proper receiver operation and to eliminate the risk of hot spots caused by blockages or regions with reduced porosity, a final foam design was developed. This new foam featured a coarser structure, with larger pores and flow channels. To achieve this, a 20 PPI foam (see Figure 34) was selected instead of the previous 30 PPI material. The lower pore density was expected to reduce the pressure drop across the receiver, thereby facilitating airflow through the porous structure. On the other hand, the reduced specific surface area associated with the lower porosity was expected to decrease the theoretical thermal performance of the receiver.

To quantify this effect, the new receiver design was modelled using a CFD approach and its performance was compared with that of the previous 30 PPI configuration. The construction parameters of both foams, together with the simulation results, are presented in Table 9. Moreover, to ensure thermal integrity of the foam and learn more about thermal behavior of the foam itself, 3 additional thermocouples were placed on the rear face of the foam as already stated above (see Figure 35).

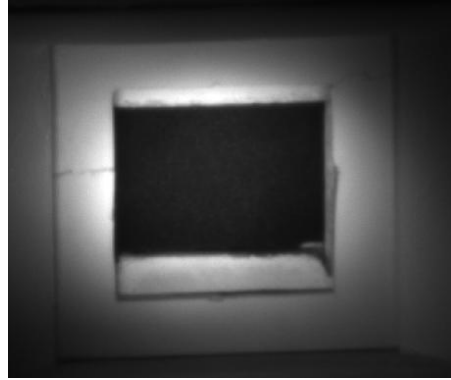
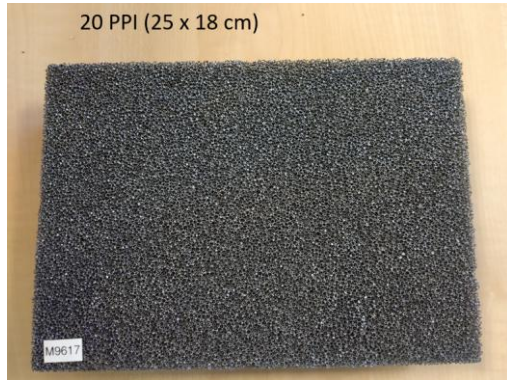


Figure 34: One of the additional 20 PPI SiSiC foam tiles before testing (left); CCD picture of test setup during testing at IMDEA (right)



Figure 35: Latest 20 PPI SiSiC foam installed and being tested at IMDEA (left); 3 additional thermocouples installed (right)

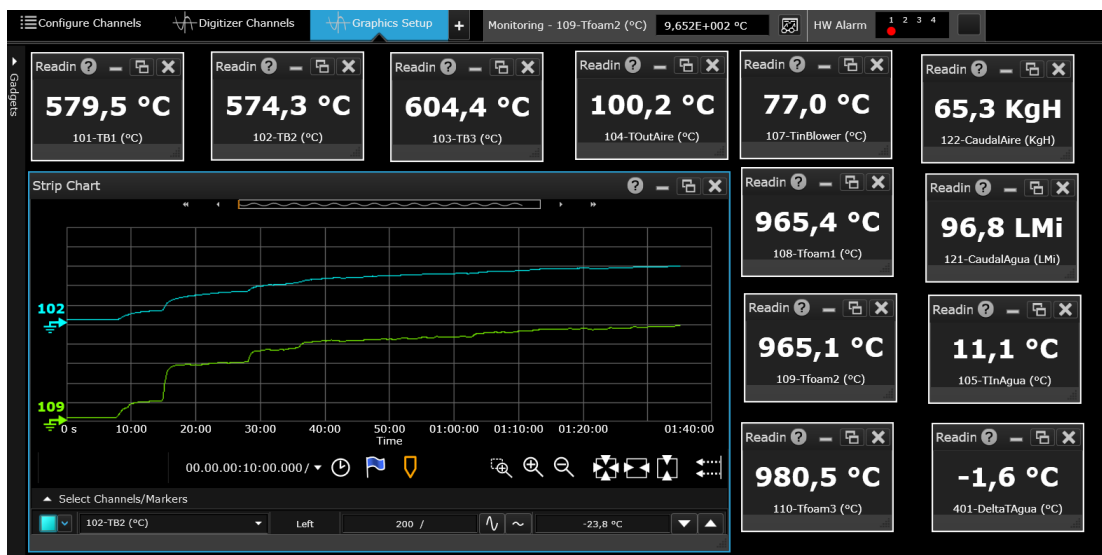


Figure 36: Screen shot of the data acquisition system temperature monitoring at IMDEA (Signals 108-110: Thermocouple readings at the rear surface of the foam; Signals 101-103: Thermocouple readings at heat exchanger air inlet; Signal 104: Thermocouple reading at heat exchanger air outlet; Signal 107: Air temperature at blower inlet; Signal 122: air flow rate; Signal 121: Water flow rate; Signal 105: Water inlet temperature; Signal 401: Water temperature difference across heat exchanger)

As can be seen in Table 9, when increasing pore size to 20 PPI, the estimated pressure drop is reduced from 272 Pa to 179 Pa. Additionally, due to the reduction in heat transfer area, the thermal efficiency is slightly reduced from about 81% to 79%, which is reasonable, given the reduced manufacturing effort, that will also reduce receiver cost substantially.

Table 9. Foam characteristic values and thermal results obtained from CFD

	30ppi	20ppi
ε	0,85	0,77
d_c (m)	0,00122	0,001963
t_s (m)	0,00019	0,000462
ΔP (Pa)	272	179
η	0,812	0,789
T_{max} (°C)	1155	1082
T_{min} (°C)	557	661
ΔT	325	148

Fortunately, with this latest foam, we were able to successfully carry out sufficient tests at different temperatures ranging from 700°C to 1000 °C at the absorber outlet. Figure 36 shows the screenshot of the temperature monitoring setup during one of the experiments at IMDEA. Figure 37 and Figure 38 present the power output results obtained during the experimental campaign conducted at IMDEA. To obtain these results, the reported values correspond to averages calculated over a 10-minute period after the receiver outlet air temperature had reached steady-state conditions.

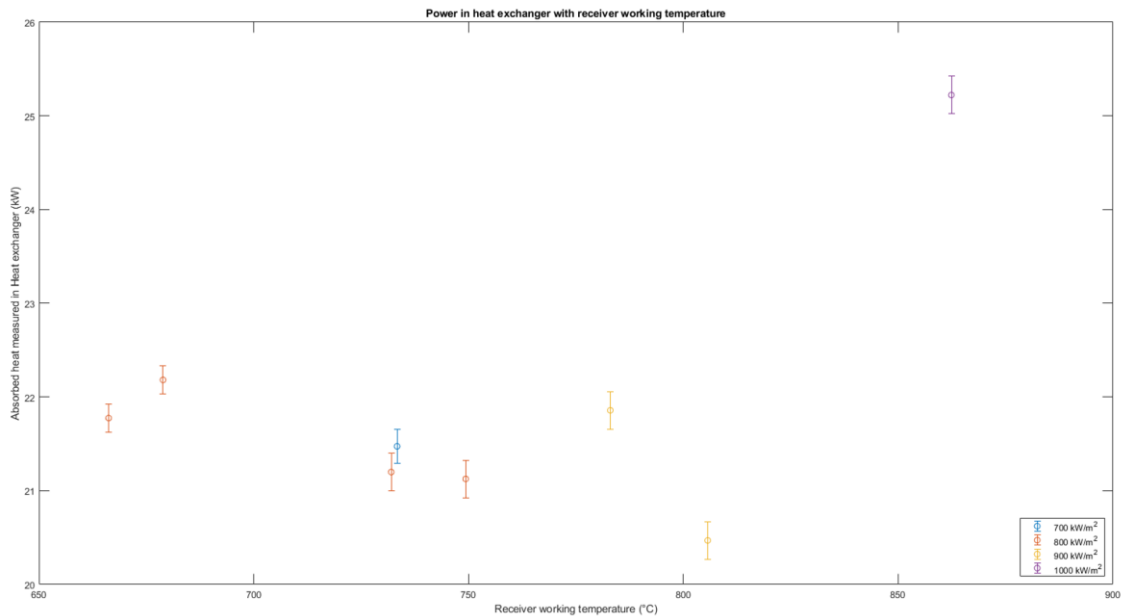


Figure 37: Thermal power absorbed in the receiver by air as a function of receiver working temperature

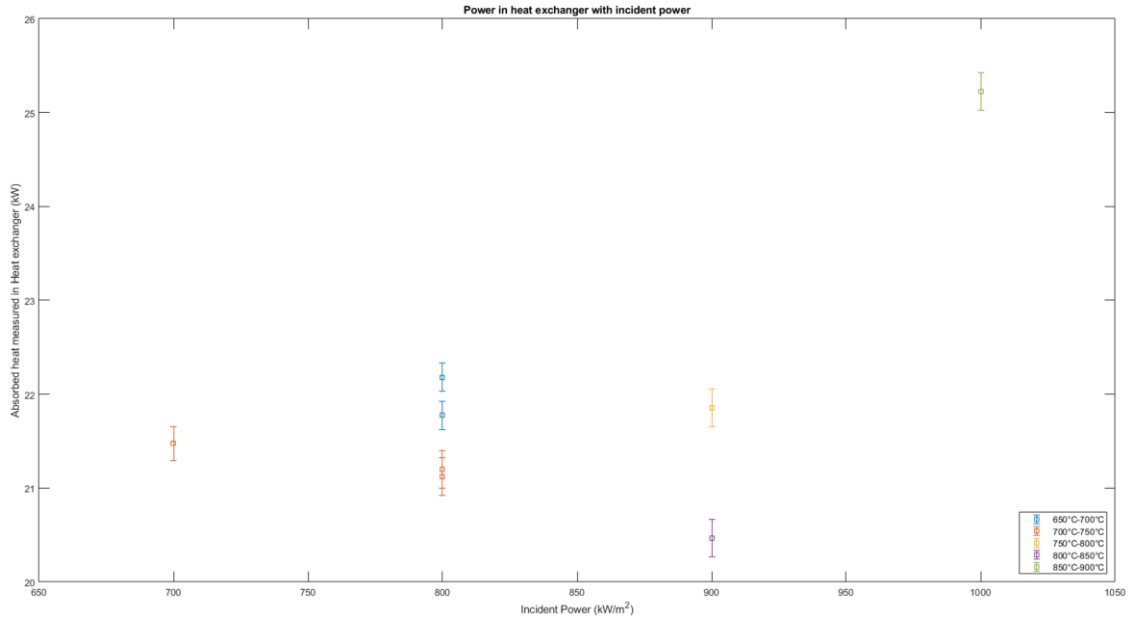


Figure 38: Thermal power absorbed in the receiver by air as a function of incident solar power

Figure 37 and Figure 38 show the thermal power absorbed by the air, calculated from the temperature and flow rate measurements performed in the air-to-water heat exchanger, together with its variation as a function of both the receiver operating temperature and the radiative flux at the foam aperture. As expected, the absorbed thermal power increases with the incident radiative flux and decreases as the receiver operating temperature rises, owing to the reduction in receiver efficiency caused by higher thermal losses at elevated temperatures. The thermal energy absorbed by the air in the receiver is slightly lower than originally expected. This is mainly due to the increase in pore size (from 30 to 20 PPI), which leads to a modest reduction in both the convective heat transfer coefficient within the foam and the specific convective surface area (m^2 of convective area per m^3 of foam). Nevertheless, this slight reduction is considered acceptable, as the experimental results demonstrate that it ensures the structural integrity of the foam under all operating conditions.

Finally, the results obtained with this latest foam absorber design, particularly in terms of thermal power and, most importantly, sufficient durability during the tests performed, demonstrate the technological viability of the foam receiver concept for the ASTERIX-CAESAR main prototype. The results provide confidence in its operation and support the deployment of the next prototype, which will be tested at the PSA during the final phase of the project.

5 Conclusions

The experimental activities presented in this document validated the performance of advanced volumetric absorber modules at progressively increasing scales. The work was divided into two complementary phases:

1. A small-scale campaign performed at the CIEMAT-PSA solar furnace (Task 6.1) at 10 kW_{th} (12 x 12 cm samples), focusing on the detailed evaluation of single absorber cups under controlled and highly concentrated solar flux, and
2. A module-scale campaign conducted at the IMDEA Energy solar tower (Task 6.2) at 20 kW_{th}, aimed at testing a 25 x 25 cm and 25 x 18 cm cup receiver under representative operating conditions.

In the following paragraphs the main findings and conclusions obtained from each campaign are summarized. Together, they provide a coherent experimental validation of the absorber technology developed, establishing a solid foundation for further upscaling and demonstration activities within ASTERIX-CAESAR.

The experimental activities conducted at the CIEMAT-PSA solar furnace successfully achieved the main objectives of Task 6.1, providing a detailed assessment of the aerodynamic, thermal and optical behaviour of the advanced volumetric absorber modules at small scale.

- The cold flow tests confirmed the aerodynamic stability of the absorber cup and demonstrated the expected dependence of mass flow rate on outlet diameter and blower speed. The 60 mm outlet configuration was selected for subsequent thermal testing, offering a balanced compromise between flow uniformity, pressure drop and structural robustness.
- The thermal performance tests validated the capability of the absorber materials to operate under high solar fluxes (up to ~1 MW/m²) and outlet air temperatures of up to 800 °C. The results revealed clear correlations between flow rate, incident power and efficiency, with diminishing returns at the highest power levels, indicating the onset of local heat-transfer limits. Across all tests, a consistent performance hierarchy emerged, identifying three/four absorbers (R1-163, R1-165 and R2-2/R2-8) as top-tier candidates. These samples achieved the highest normalized efficiencies and demonstrated excellent reproducibility across the full range of operating conditions. The important conclusion is that the new low-cost recipe (R2) behaves very similar to the already proven CAPTURE recipe (R1), validating its suitability for the final ASTERIX-CAESAR prototype.
- The optical characterization performed before and after thermal cycling confirmed that all absorbers maintained high solar absorptance ($\alpha \approx 0.95\text{--}0.97$) and moderate thermal emittance ($\varepsilon \approx 0.94\text{--}0.96$ at 800 °C) with negligible degradation after repeated exposure. These findings demonstrate the strong optical and thermal stability of the absorbers and materials, essential for long-term durability in solar receiver environments.

Overall, the PSA campaign provided a robust and coherent dataset supporting the reliability of the new absorber designs and the validity of the test methodology. The results constitute a solid foundation for the next experimental phase, aimed at validating the absorber performance under more representative receiver conditions at larger foam tile size.

The module-scale tests at IMDEA have yielded the following conclusions:

- 30 PPI foam samples cannot be easily upscaled to above 20 x 20 cm of tile size. Manufacturing issues lead to blocked pores and make the foam samples unsuitable for the application as volumetric solar absorber. They heavily oxidize due to blocked air flow.
- We need to select at least 20 PPI instead of 30 PPI (CAPTURE project reference). PPI is the acronym for pores per inch. The higher the PPI number, the smaller is the pore size. By increasing pore size to about 20 PPI, the manufacturing is simplified and the problem of blocked pores is solved. The slight decrease in receiver efficiency is outweighed by the reduction in production cost. The exact impact of cost reduction will be analysed in detail until project end.
- Besides the decision for larger pore sizes, a second alternative material will be used at the final receiver prototype: Silicon Infiltrated Silicon Carbide (SiSiC). SiSiC can be easier manufactured because of no shrinkage, but the oxidation resistance is lower. Thus, two sets of foams are being manufactured for the final receiver prototype: One set of sintered SiC and another set of SiSiC. Both sets will be tested. In parallel, the manufacturing route of the sintered SiC will be continuously improved until project end.
- The final samples² of size 25 x 18 cm have worked well during the experiments performed in early summer 2026. This has demonstrated the technological viability of the foam receiver concept for the ASTERIX-CAESAR main prototype. The results provide confidence in its operation and support the deployment of the next prototype, which will be tested at the PSA during the final phase of the project. The upcoming final receiver tests should further validate the oxidation resistance during the experimental activity in the final project year.

² Note that the rectangular shape is determined by the existing receiver casing. 16 modules will fill the existing CAPTURE receiver casing.

References

- [1] F. Zaversky, I. Les, P. Sorbet, M. Sánchez, B. Valentin, F. Siros, J.-F. Brau, J. McGuire, and F. Berard, "CAPTURE Concept Specification and Optimization (Deliverable 1.4)," ed. <https://cordis.europa.eu/project/id/640905/results>: European Commission, 2020.
- [2] W. E. C. Pritzkow, R. S. M. Almeida, L. B. Mateus, K. Tushtev, and K. Rezwan, "All-oxide ceramic matrix composites (OCMC) based on low cost 3M Nextel™ 610 fabrics," *Journal of the European Ceramic Society*, vol. 41, pp. 3177-3187, 2021/05/01/ 2021.
- [3] M. Ahmed, H. Park, C. K. Bach, and O. San, "Numerical investigation of air mixer for HVAC testing applications (ASHRAE RP-1733)," *Science and Technology for the Built Environment*, vol. 26, pp. 1252-1273, 2020/10/20 2020.
- [4] Siltherm-Europe-Limited, "Siltherm Board - Rigid Microporous Insulation," ed. Sandyford Business Park, Dublin, Ireland, 2019.
- [5] A. L. Avila-Marin, M. Alvarez de Lara, and J. Fernandez-Reche, "Experimental results of gradual porosity volumetric air receivers with wire meshes," *Renewable Energy*, vol. 122, pp. 339-353, 2018/07/01/ 2018.
- [6] B. Hoffschmidt, R. Pitz-Paal, M. Böhmer, T. Fend, and P. Rietbrock, "200 kWth open volumetric air Receiver (HiTRec) of DLR reached 1000 °C average outlet temperature at PSA," *J. Phys. IV France*, vol. 09, pp. Pr3-551-Pr3-556, 1999.
- [7] F. M. Téllez, M. Romero, and M. J. Marcos, "Design of "SIREC-1" Wire Mesh Open Volumetric Solar Receiver Prototype," in *ASME 2001 Solar Engineering: International Solar Energy Conference (FORUM 2001: Solar Energy — The Power to Choose)*, 2001, pp. 357-364.