# Experimental Testing of a 300 kWth Open Volumetric Air Receiver (OVAR) Coupled with a Small-Scale Brayton Cycle. Operating Experience and Lessons Learnt

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**Abstract.** This paper summarizes the objectives and experimental activity of the H2020 research project CAPTure, which officially lasted from May 2015 to July 2020. The main objective of the CAPTure project was the development and testing of several key components that allow the implementation of a solar powered combined cycle plant (topping Brayton cycle and bottoming Rankine steam cycle). The main innovation was related to the coupling of the open volumetric air receiver (OVAR) with the pressurized air stream of the Brayton cycle, i.e. the external heating of the Brayton cycle with hot air at atmospheric pressure. One key component was therefore a gas-gas heat exchanger, which was implemented as regenerator (atmospheric heating – pressurized cooling). A 300 kWth prototype, consisting of the solar receiver, the regenerative system and a small-scale Brayton cycle, was designed and implemented at CIEMAT-PSA. The paper describes the CAPTure prototype and the experimental activity performed until September 2021.

## INTRODUCTION

The CAPTure (Competitive SolAr Power Towers) H2020 project lasted from May 2015 to July 2020 and focused on an innovative central receiver CSP plant configuration, investigating the application of an open volumetric air receiver (OVAR) for heat generation at highest temperature in order to power a combined cycle (CC) – topping Brayton, plus bottoming steam Rankine cycle – for efficient and competitive renewable power generation. The investigated power plant layout [1] is shown in Fig. 1. The power plant key components, most critical for future commercial implementation, are (i) the CAPTure open volumetric air receiver (OVAR), and (ii) the CAPTure regenerative system coupling the high-temperature atmospheric air stream with the pressurized air loop of the topping Brayton cycle. This approach decouples the high temperature and the high heat flux part (solar receiver) from the high pressure part (compressed air stream of the Brayton cycle) via an air-air regenerative heat exchanger. Thus, upstream the CC, the well proven and relatively cheap regenerator-type heat storage can be used. An additional low-temperature air/rock thermocline TES is proposed in order to reuse the return air heat in regenerative manner (hence without recirculation to the receiver). The most critical implementation step is clearly the coupling of the solar receiver's atmospheric air stream with the topping Brayton cycle via the regenerative heat exchange unit, heating the Brayton cycle externally (Fig. 2). Therefore, one of the CAPTure project's main objectives was to validate these most critical components in the relevant environment. Accordingly, a 300 kWth prototype was designed, built and operated at CIEMAT-PSA in the south of Spain (see prototype 3-D view in Fig. 3, left).

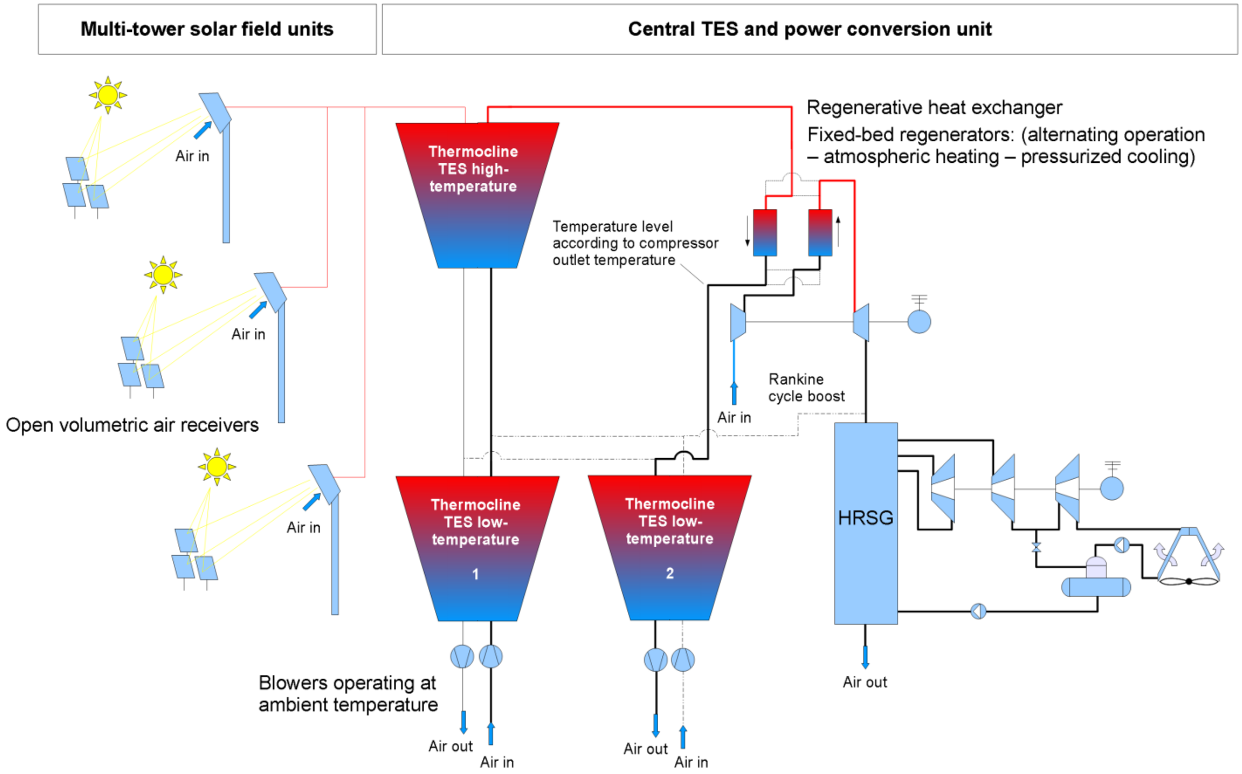


**FIGURE 1.** Scheme of the CAPTure solar powered combined cycle plant with high-temperature TES upstream the gas turbine [1, 2]

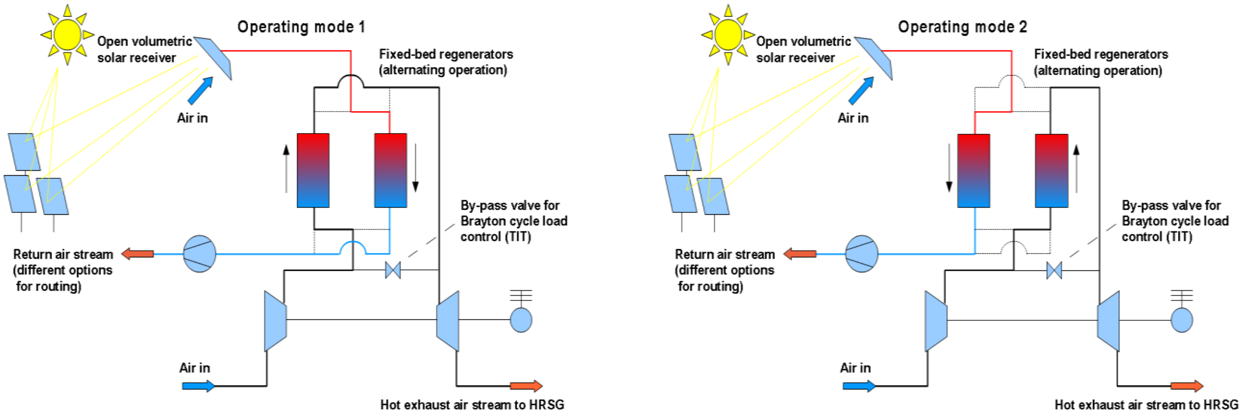


**FIGURE 2.** CAPTure concept scheme of alternating operation of fixed-bed regenerators in order to exchange heat between atmospheric (receiver) and pressurized air stream (Brayton cycle) [1, 2]

## Advantages and Limitations of the CAPTure Regenerative Air-Air Heat Exchange System

As already mentioned above, one of the most critical components of the proposed power plant concept (Fig. 1) is the needed high-temperature gas-gas heat exchanger in order to power the topping Brayton cycle externally. As the coefficient of heat transfer on the atmospheric air side is very limited, the design of such a heat exchanger is expected to be very bulky, since a large area of heat transfer is needed. In principle, a shell-and-tube heat exchanger design is expected [3], having the pressurized air stream coming from the Brayton cycle's compressor on the tube side, and the heating air stream at ambient pressure (coming from the TES) on the shell side. This type of heat exchanger could be similar to a heat recovery steam generator, but using metal alloys with higher temperature and oxidation resistance. In order to counterbalance the issue of low heat transfer coefficient, a very large area of heat transfer would be needed. This is the reason why heat recovery steam generators of combined cycle plants are very bulky and represent an important share of the power block's CAPEX. The same holds for the air-air heat exchanger that is needed for the CAPTure power plant layout (see Fig. 1). Therefore, in order to reduce size and cost of the air-air heat exchanger, the application of a regenerative heat exchange system (atmospheric heating, pressurized cooling) is proposed. Regenerators are well known for high specific heat transfer areas and very high heat exchange effectiveness [4]. Also, when ceramic material is used as regenerator matrix, substantial cost savings can be achieved with respect to conventional shell-and-tube heat exchangers of same power rating. For example, cordierite ceramic honeycomb structures (as widely applied in catalytic converters and high temperature gas filtration, etc.) are orders of magnitude cheaper than high-temperature alloys that would be needed for the high-temperature shell-and-tube heat exchanger design.

However, when looking at the specific application of heat exchange between two air streams at different pressures, there are important design limitations. First, the vessel size of this regenerative heat exchange system is limited due to the pressurization process (the higher the vessel volume, the longer the time needed for pressurization), which requires several two-vessel subunits (such as shown in Fig. 1 and Fig. 2) in parallel, depending on the power rating and cycling period duration. The second reason for several two-vessel subunits in parallel is the requirement for continuous thermal power transfer (while one system is pressurized/depressurized, the parallel systems need to take over). Thus, one disadvantage w.r.t. conventional heat exchangers is the higher complexity, as besides several parallel systems also high-temperature valves and piping are required for managing the pressurization/de-pressurization process. Furthermore, the pressurization process requires a certain amount of work, i.e. represents an additional parasitic consumption. Additionally, the flow cross section of the atmospheric ducts is considerably bigger than that of the pressurized circuit, which complicates the design. It must also be emphasized that the required high-temperature valves for managing the complex air flow have a clear upscaling limit, which also depends on the valve type applied. For example, the upper manufacturing limit for the ceramic valve ball leads to a maximum flow cross section size of about DN 200. The flow cross section may be increased to DN 400 when applying a butterfly-type valve with ceramic butterfly flap. This means that for upscaling of the CAPTure plant concept, several valves need to be applied in parallel ducts in order to achieve the nominal air flow rate at acceptable pressure drop. Clearly, these disadvantages need to be offset by higher heat exchange effectiveness and reduced heat exchanger size and cost (with respect to the conventional shell-and-tube layout). Due to the abovementioned and additional design constraints (see Ref. [2]), the CAPTure power plant concept seems to be viable only at small power classes.

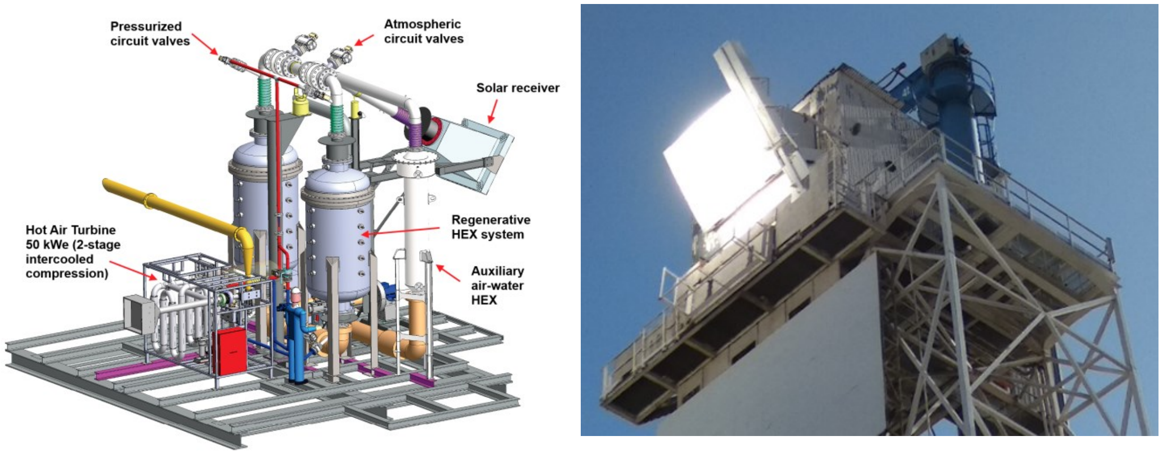


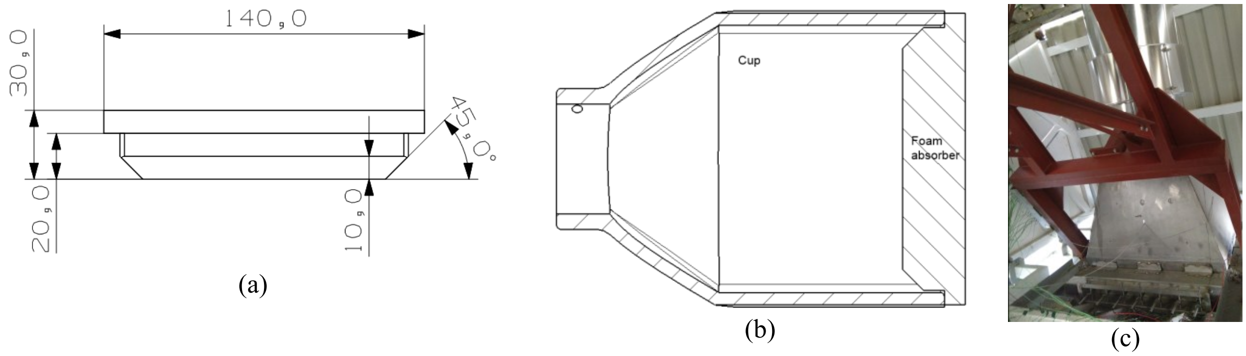
**FIGURE 3.** CAPTure validation prototype 3-D view (left); Receiver during on sun testing (right)

# DESCRIPTION OF THE PROTOTYPE COMPONENTS

The 3 main components, described in the following, are (i) the solar receiver, (ii) the regenerative heat exchange system including valves, and (iii) the small-scale Brayton cycle (hot air turbine). These main components are connected via atmospheric and pressurized circuit piping, as shown in Fig. 3 (left). The atmospheric air piping (DN200) as well as the pressurized circuit piping (DN50) is externally insulated. The chosen piping material for all high-temperature parts (900ºC nominal operating temperature) is AISI 310S. As the solar receiver and the regenerative heat exchanger vessels are internally insulated, special interface components were designed, which allow the transition from internal to external insulation. This is a specific feature of the prototype; for future implementation, a unique insulation concept may be chosen.

## The CAPTure Open Volumetric Air Receiver

The CAPTure solar receiver design (developed by CENER) is modular, based on individual absorber cups, with ceramic foam of porous SSiC (pressureless sintered Silicon Carbide) as solar absorber material (see Fig. 4); in contrast to honeycomb-type ceramic solar absorbers used previously [5, 6]. The solar receiver design is similar to previous research projects [5, 6], 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 [7]. Zones with higher incident flux density need higher air flows, thus lower flow resistance (e.g. larger orifice diameter). The aim is to achieve the same air outlet temperature for all cups. Unlike previous projects, the CAPTure solar receiver was designed without air recirculation, i.e. there is 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 [5]). The CAPTure receiver has an aperture area of 0.706 $m^2$ and is composed of 35 individual cups, each having dimensions of 140 x 140 mm (see Fig. 4). It has a nominal thermal power of about 300 kW. For performance evaluation, thermocouples are placed inside each cup and also after the receiver exit flange, in order to measure the effective receiver outlet temperature (mixing temperature of all individual cup streams). The receiver consists of an internally insulated stainless steel box constructed using sheet metal. Figure 4 (c) displays the rear view of the receiver at the top testing level of SSPS-CRS experimental tower at CIEMAT-PSA. The incident solar flux coming from the solar field has been measured applying a Lambertian moving bar and a fixed Gardon radiometer installed right next to the receiver aperture [8].



(a)

(b)

(c)

**FIGURE 4.** Foam geometry side view (a) with 30 mm total thickness and 10 x 10 mm frustum [9] – Absorber cup and foam cross sectional view (b) – CAPTure receiver mounted; inside view in tower test room (c)

## The CAPTure Regenerative Heat Exchange System

The regenerative heat exchange vessels are shown in Fig. 5. They are internally insulated pressure vessels, containing a matrix of cordierite ceramic honeycomb bricks. The height of the vessels from top to bottom flange is about 3 m. The free internal diameter is roughly 1 m. The internally insulated design allows the application of standard carbon steel for the pressure vessel, since the maximum temperature of the vessel can be kept at about 50ºC, while the internal volume is designed for 900ºC operating temperature.

A thermocouple tree was installed during the installation process of the cordierite honeycomb bricks, which allows the monitoring of the temperature evolution inside the regenerative matrix, in both axial and radial directions, during operation. The regenerative system was designed and implemented by project partner Tekniker.

Besides the two identical regenerator vessels, the regenerative heat exchange systems also includes 8 valves (4 large diameter – DN200 – atmospheric valves, and 4 small diameter – DN50 - pressurized circuit valves) that allow the individual charging, discharging and switching operation between operating states. The valves are of ball valve type and use ceramic balls on the high-temperature side (regenerator top: receiver outlet and turbine inlet) and metallic balls on the low temperature side (regenerator bottom: blower inlet and turbo charger outlet). The valves are pneumatically actuated and were provided by project partner Samson Cera System.

**FIGURE 5.** Picture of the two CAPTure regenerative heat exchange vessels and parts of air piping in the tower test room.

## The CAPTure Small-Scale Brayton cycle (Hot Air Turbine)

The CAPTure small-scale hot air turbine for power generation is a bespoke design based on heavy duty turbo-charger technology applying radial turbomachinery. It consists of a low pressure turbocharger unit, a high pressure turbo charger unit, an intercooler between the two compression stages, and a power turbine (see Fig. 6, showing the prototype scheme). All hot air turbine components, including the inter cooler, were mounted on a metal frame as shown in Fig. 7. The hot air turbine unit was designed and implemented by project partner Bluebox Energy Ltd. The small-scale hot air turbine unit has a nominal power output of roughly 50 kW. The maximum turbine inlet temperature for short-term testing is 850ºC, and 750ºC for long-term operation. The pressure ratios of low pressure and high pressure compressor stages are about 3. The nominal air mass flow rate is about 0.4 kg/s. The hot air turbine unit was planned to be started using pressurized air exiting a starting nozzle right before the low pressure compressor inlet (see Fig. 7-b). The air starting nozzle was expected to induce enough mass flow across the turbomachinery, the piping, and the regenerative matrix in order to raise turbine inlet temperature and reach self-sustain conditions of the power cycle.

Unfortunately, after various failed turbine start-up experiments, it was clear that the flow resistance across the regenerative system (including piping and valves) was too high and the mass flow induced by the air start nozzle was too low to achieve the needed TIT for self-sustain conditions. Therefore, an auxiliary air blower was installed and connected to the low-pressure turbocharger inlet, with the objective to increase the air mass flow during start up, being able to reach self-sustain conditions. It is clear that this start-up issue should have been detected during the design procedure when performing the start-up simulations among involved project partners. Unfortunately, due to too idealized pressure drop assumptions, the issue was not detected on time. A rather simple solution would have been to increase the flow cross section of the pressurized circuit piping. Also, the sections dedicated to flow separation and joining of pressurized and atmospheric piping should have been optimized more thoroughly applying CFD simulations. It must be said that these last statements should not lessen the demanding engineering work during the design phase; they should rather give valuable hints for future research work; with the benefit of hindsight one is always wiser.

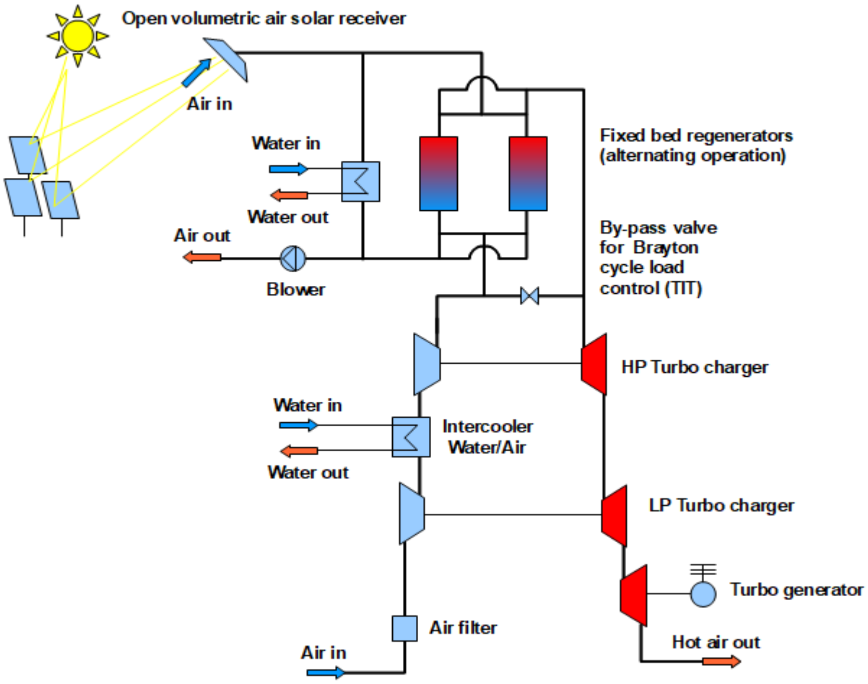


**FIGURE 6.** CAPTure prototype scheme including the auxiliary air/water heat exchanger (for receiver only operation) and the intercooled small-scale hot air turbine (low pressure turbo charger, high pressure turbocharger and power turbine).

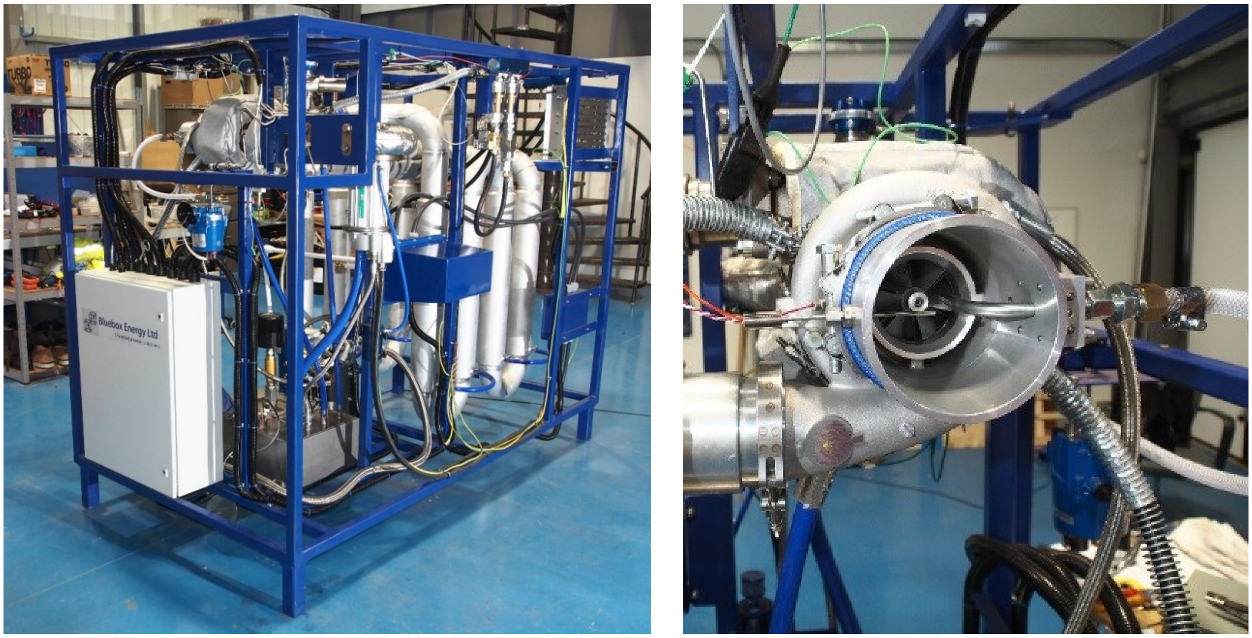

(a) (b)

**FIGURE 7.** Hot air turbine mounted in a metal frame ready for installation in the tower test level (a); View of the low pressure turbo charger inlet showing the air start nozzle (b)

# EXPERIMENTAL ACTIVITY

The prototype integration work started in February 2019, beginning with structural reinforcements of the tower's testing level and the lifting of the regenerator vessels and prototype main support structure. The integration work was a very demanding task due to the limited space in the tower and the complex piping arrangements. The tricky 3D puzzle was bravely mastered by project partner TSK with important support provided by CIEMAT-PSA.

The CAPTure prototype is operational since February 2020, beginning with the solar receiver on-sun testing (see Fig. 3 - right, and Fig. 8). The CAPTure solar receiver has been tested during more than 100 operational hours, achieving maximum receiver outlet temperatures (mixing temperature) just below 800°C, with maximum temperatures observed at cup level (individual absorber outlet temperature) exceeding 900°C, approaching 1000°C. The solar receiver has shown very stable operation without damage or visual degradation so far. Nevertheless, as the testing is not yet completed, a detailed analysis of absorber degradation in the laboratory is still pending. This will be done once the tests are finished and the receiver's absorber modules can be disassembled.

Concerning the solar receiver's operating temperature, it needs to be distinguished between the maximum temperature observed in the individual solar absorbers (cups) and the mixing temperature at the rear flange of the receiver. While the maximum operating temperature observed during operation was between 950 and 1000 °C at cup level, the effective receiver outlet temperature was always substantially lower due to the shape of the flux distribution. Unfortunately, the aiming strategy needed to be adapted several times such that the air flow adjustment was not the ideal one. The absorbers located in the center of the aperture area achieved substantially higher outlet temperature than the absorbers close to the aperture circumference. Therefore, when designing a demonstration-scale receive as a next step, the air flow distribution needs to be well designed according to the final flux profile.

At this point, since the testing procedure is not yet completed, no final well-justified conclusion can be given regarding the receiver efficiency at relevant operating temperatures. First, the measurement uncertainty is very high. Secondly, since the air flow distribution is not optimized for the finally applied aiming strategy, the experimental efficiency, based on the effective receiver outlet temperature, will always be substantially lower than that for the case with optimized air flow distribution.

**FIGURE 8**. SSPS-CRS experimental tower at CIEMAT-PSA during on-sun testing of the CAPTure prototype

Also, the CAPTure regenerative system was charged and discharged, gradually increasing operating temperature, carefully observing temperature gradient limits, in order to guarantee the integrity of the ceramic regenerative matrix. Charge and discharge operation worked as expected during atmospheric pressure testing.

Finally, once regenerator charging temperatures close to the self-sustain conditions (≈650ºC) of the CAPTure hot-air turbine were reached, also the hot air turbine circuit was activated and several turbine start-ups were initiated, by activating the air-start nozzle, which injects pressurized air in the compressor intake duct, hence speeding up the compressor wheel and inducing the needed air flow across the regenerative system and the turbine stages. Unfortunately, no stable self-sustain turbine operating point could be reached so far, due to the following issue: The pressure drop across the regenerative system's discharge loop (small diameter pressurized circuit) seems to be too high during the start-up, i.e. pressurization phase, such that the needed mass flow and turbine inlet temperature cannot establish. Neither the application of the added auxiliary start-up air blower could solve the issue so far.

Additionally, several issues with the regenerative system's valves were observed, where small particles from other prototype components (e.g. insulation material, flanges, solar receiver or regenerator matrix) or dirt were hindering correct valve actuation. Thus, the experimental activity had to be stopped several times and valves cleaned. Although the CAPTure project has already finished (no more EU funding), the consortium will continue testing activity, at least during 2021, with the objective to finally achieve stable turbine operation.

## CONCLUSIONS AND OUTLOOK

Taking into account the difficulties encountered during the design and implementation phase of the CAPTure prototype, the issues related to turbine start-up, as well as the results of the techno-economic optimization and benchmarking [1, 2] of the CAPTure power plant concept, unfortunately, it must be concluded that the solar powered combined cycle cannot compete with much simpler power plant layouts. The results of the CAPTure project indicate that a conventional Rankine single-cycle plant seems to be the better choice. The combined cycle seems to be only attractive for very small power tower plants (below 5 MWe). Although gas turbines can be scaled down quite well having a reasonable performance at small power classes, this is not the case for Rankine steam cycles. Hence, when thinking of very small (i.e. “micro”) combined cycles, the application of the organic Rankine cycle (ORC) as bottoming power cycle should be considered. This concept could be attractive for small and modular CSP central receiver plants for “electricity islands”, i.e. small remote grids, where electricity price is very high. In this context, it should be noted that this outcome is very much in line with the objectives of the H2020 project POLYPHEM [10].

Nevertheless, a very promising alternative high-efficiency power plant concept, which could make use of the components developed in the CAPTure project, would be the combination of compressed air energy storage (CAES) and CSP. Here, the interested reader is referred to Ref. [11].

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the great work and indispensable contributions of all involved staff of CIEMAT-PSA and TSK that superbly mastered the very demanding prototype integration work at the top of SSPS-CRS tower, as well as the experimental activity. Furthermore, the authors gratefully acknowledge the valuable contributions of ACE Refractory International, S.L, who provided among other sub-components the solar receiver’s radiation shield.

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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