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A Cost-Effective Open Volumetric Air Receiver Design Based on Free Floating Stackable Absorber Modules

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Abstract. The CAPTure Open Volumetric Air Receiver (OVAR) design is based on ceramic stackable "free floating" absorber modules that form the receiver structure and avoid a complex metallic double membrane design. The novel receiver design has been validated at small-scale (15 kW_{th}) at a solar simulator, as well as on the top of an experimental tower at 300 kW_{th}, up to absorber module outlet temperatures above 900ºC. The novel OVAR concept is attractive for both the concentrated solar power (CSP) sector, as well as for high-temperature process heat supply. The thermal efficiency of the receiver concept is expected to be above 80% at outlet temperatures of 900ºC.

Keywords: CSP, High-Temperature Process Heat, Ceramic Foam Receiver

1 Introduction

The CAPTure (Competitive SolAr Power Towers) H2020 project lasted from May 2015 to July 2020 and was focused on an innovative central receiver CSP plant configuration, investigating the application of an open volumetric air receiver (OVAR) for heat supply at highest temperature (≈ 1000ºC) in order to power a combined cycle (CC) – topping Brayton, plus bottoming steam Rankine cycle – for efficient and competitive renewable power generation [1]. Due to an innovative air-air heat exchange system, it is possible to externally heat the topping Brayton cycle using an OVAR without the need of a pressurized air receiver. This approach is highly advantageous for three reasons: (i) no fragile quartz window is needed, (ii) higher efficiencies and flux densities compared to tubular or opaque heat exchanger type receivers can be achieved, and (iii), a very cost effective thermal energy storage (TES) system can be installed upstream the gas turbine [1], allowing dispatchable operation of the power cycle, a must for CSP.

The beginning of the research line of ceramic OVAR technology dates back to the 1980's [2] and led to three main development projects called HiTRec I, HiTRec II [3] and SolAir [4]. The design principle was based on a modular approach [3], where the receiver aperture was formed by a matrix of small (≈ 14 cm width) ceramic absorber modules placed next to each other with small spacing between them. The ceramic absorber modules (honeycomb absorber and ceramic cup) were mounted in a metallic double-membrane base structure that allowed the circulation of return air. The developed receiver design was successfully tested and validated experimentally. The promising results led to the construction of the demonstration plant at DLR in Jülich [5].

The return air stream is primarily needed in order to guarantee sufficient cooling of the metallic double membrane structure at high-temperature operation [3]. An additional need arises when considering the power plant's overall performance, e.g. considering the basic power plant layout as shown in Fig. 1. From the thermodynamic point of view, the air exiting the heat recovery steam generator (HRSG) should be recirculated to the receiver in order to reuse the low-temperature heat (typically between 100 and 200 ºC depending on power cycle architecture and pinch point in the HRSG). However, the percentage of achievable air recirculation is very limited and typically below 50% [3], meaning that more than half of the recirculated low-temperature heat is lost to the environment.

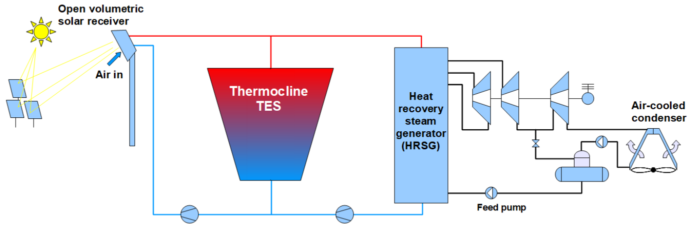


Figure 1. Basic CSP plant configuration with OVAR, TES and Rankine steam cycle. Plant concept according to [5].

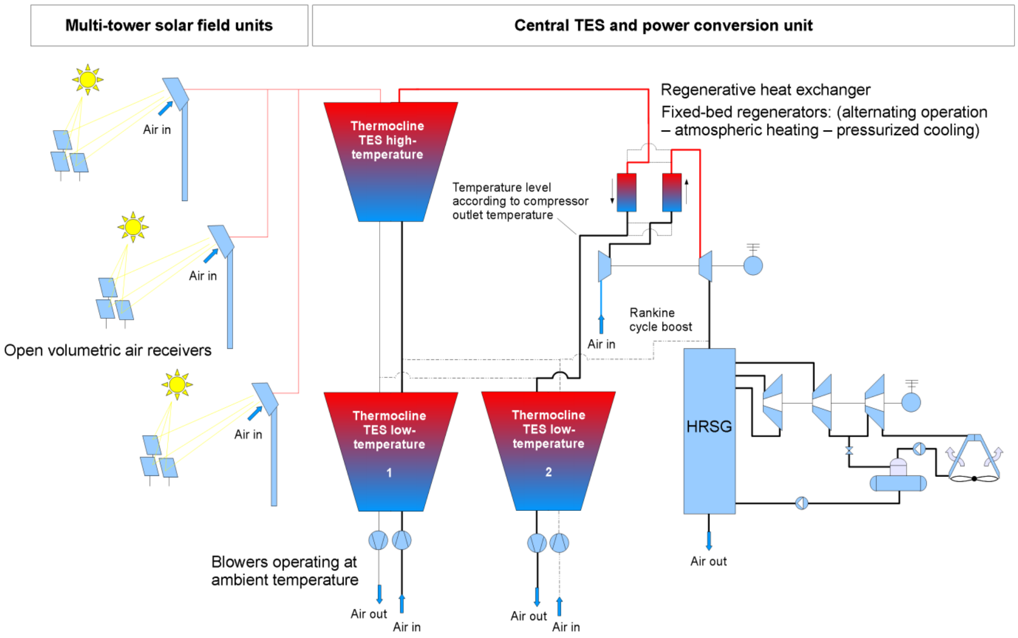


Figure 2. CAPTure Solar powered CC scheme with open volumetric air receiver and high-temperature TES (without reheat in the Brayton cycle) – The low-temperature TES enables regenerative use of return air heat [1].

The CAPTure project started from the developments made in previous OVAR projects, but proposed an alternative power plant configuration where the OVAR is thought to heat a Brayton cycle externally (solar powered CC plant configuration – Fig. 2). Since the CC's thermodynamic average temperature of heat input is significantly higher than that of the simple Rankine cycle plant, the return air temperature is higher (function of Brayton cycle pressure ratio) and it is thus not feasible to recirculate the return air to the solar receiver. Additionally considering that more than half of the return air energy would be lost to the environment (realistic air return ratio < 50% [3]) in any case, the CAPTure OVAR was designed without air recirculation. A low-temperature TES unit allows the utilization of the return air heat.

2 The novel OVAR design based on free floating stackable absorber modules

The CAPTure OVAR technology is a simplified version of that developed in previous OVAR research projects [3-5]. The key modification is that no return-air stream is implemented due to a different power cycle architecture. The receiver design is also modular, based on individual absorber modules (cups), using ceramic foam of porous SSiC (pressure-less sintered Silicon Carbide) as solar absorber material (Fig. 3 and Fig. 4), in contrast to honeycomb-type ceramic solar absorbers used previously [3-5]. Each cup contains the solar absorber matrix. The modular design is required for two reasons:

- Ideally, the solar absorber should be exposed to uniform solar flux in order to avoid local overheating and thermal stress that could lead to absorber failure; the modular design approximates uniform flux conditions at absorber module scale.
- The modular design is required to adjust the mass flow locally (different air outlet geometry for each cup) according to the given solar flux map. Zones with higher incident flux density need higher air flows, thus lower flow resistance (e.g. larger outlet orifice diameter or variable foam thickness). The aim is to achieve the same air outlet temperature for all absorber modules.

The novel approach of the CAPTure receiver is that the design is considerably simplified compared to previous research projects [2, 3], where a very complex metallic double membrane structure was used to serve as absorber module mounting structure. Ideally, the whole receiver and absorber structure should be of ceramic material in order to reduce complexity of thermal insulation and costs. The CAPTure design applies the novel concept of "*free floating*" absorber modules. The idea is that the ceramic absorber modules themselves, in stacked configuration, form the receiver structure only exposed to compression loading in the vertical walls. Ceramic materials are most resistant to compression loading, while bending stress and tensile stress should be avoided. At the same time, the compression loading must be kept within limits, such that thermal expansion does not introduce additional stress to the existing compression stress due to the weight of the absorbers. Therefore, thermal expansion must be taken into account, and all absorber modules of the receiver must be able to expand freely according to their specific temperature distribution and heat load. The design concept is based on stackable, "*free-floating*" ceramic modules that are arranged in vertical columns. Each column is able to freely expand upwards during thermal expansion of the modules (Fig. 3). Additionally, the free gap between each column is the space needed for free thermal expansion in horizontal direction. The vertical movement and the correct horizontal position of each column is guaranteed by a set of guiding elements, which are in this specific implementation proposal, ceramic tubes. This design has not only advantages with respect to simplicity of design, but also regarding reduced thermal stress loading of individual absorber modules, reducing the risk of failure. A target cost of below 25 k€ per m^2 of receiver aperture is envisaged.

In order to easily replicate the receiver at different nominal power classes, the proposed up-scaled receiver design is modular as well. The complete receiver is composed of an even number of receiver sub-modules until the corresponding nominal power is achieved. The size of one receiver sub-module is defined by the maximum number of cups that can be stacked on top of each other (compression strength limit). A reasonable size would be a maximum stacking height of about 3 meters, taking into account the assembly process where at least two operators need to install the receiver cup columns inside the receiver aperture. In this case, ceramic tubes of about 3.5 meters length would be needed. The optimum stacking height still needs to be determined and will be subject of future development projects.

The maximum width of the receiver sub-module would be defined by structural limitations of the horizontal beams of the receiver main frame (see Fig. 3). A receiver sub-module width of up to 6 meters seems reasonable at the first sight. In any case, these maximum dimensions may be varied according to the specific total nominal solar power and is thus project specific. Therefore, a typical size of one sub-module would be about 18 m^2 (6 m x 3 m), falling approximately into the 5 MW$_{th}$ power class. The final receiver would then be composed of several identical 5 MW$_{th}$ units. Figure 3 displays the concept having two receiver sub-modules placed on top of each other.

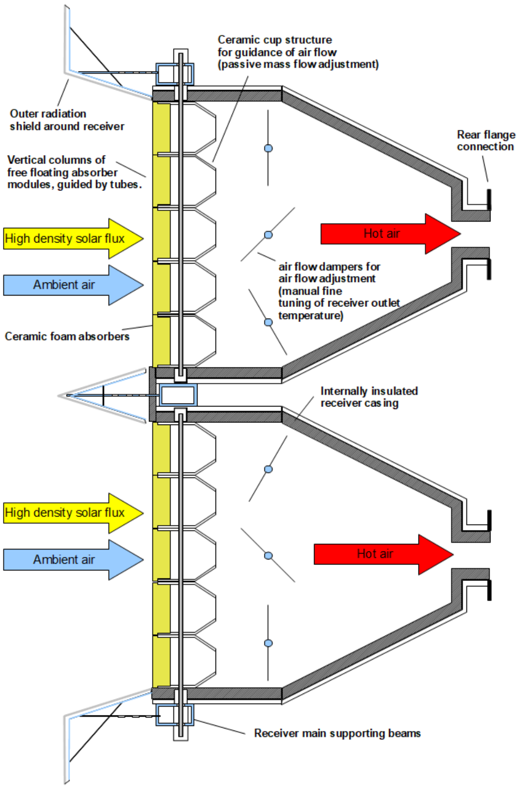


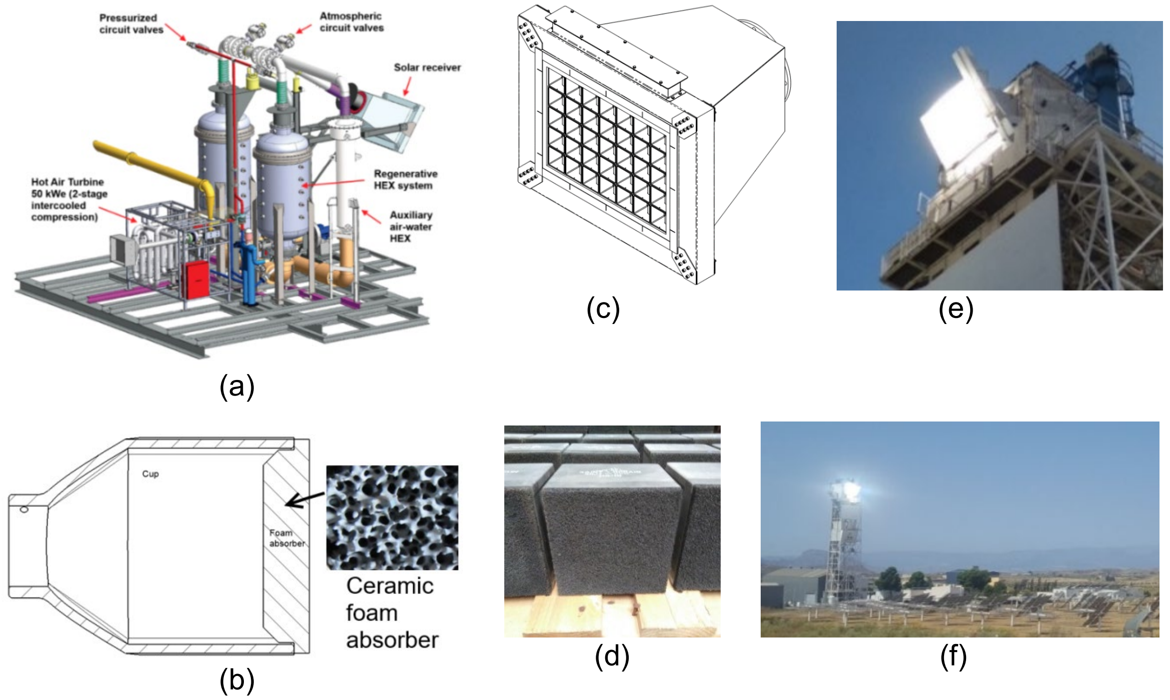
Figure 3. CAPTure Open Volumetric Air Receiver (OVAR) concept.

The outer metallic receiver casing is internally insulated with high-performance insulation material, leading to maximum outer shell temperatures of about 50 °C at receiver design operating temperatures of up to 900 °C. The receiver's structural main frame (horizontal and vertical steel beams) is protected from incident solar flux via adequate radiation shields (see Fig. 3).

3 Experimental validation

In the CAPTure research project [6], the above described receiver design concept has been successfully built and tested at a thermal power of 300 kW$_{th}$. The receiver was tested together with a regenerative heat exchange system and a small-scale hot air turbine [6] (see Fig 4 - a). The CAPTure receiver has an aperture area of 0.706 m^2 and is composed of 35 individual cups (see Fig. 4 – b and c), each having dimensions of 140 x 140 mm (see Fig. 4 – b and d).

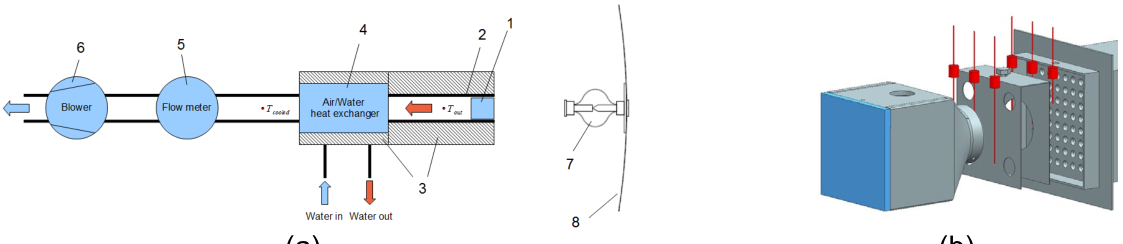
Figure 4 (e and f) show solar receiver on-sun testing at CIEMAT-PSA. The absorber parameters are as follows: absorber depth = 30 mm, cell diameter = 1.122 mm, strut thickness = 0.195 mm, porosity = 0.87, $\boldsymbol{\alpha}$ = 0.9, $\boldsymbol{\varepsilon}$ = 0.8 [1]. The CAPTure solar receiver has 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.



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

Figure 4. CAPTure Open Volumetric Air Receiver (OVAR) experimental validation.

The solar receiver has shown very stable operation without damage or visual degradation, so far. 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. The absorbers located in the center of the aperture area achieved substantially higher outlet temperature than the absorbers close to the aperture circumference, a typical behavior that must be addresses with corrected design of flow resistance for future implementations. Due to the inhomogeneous air outlet temperature at cup level, no reliable experimental confirmation of the receiver efficiency could be obtained during the CAPTure project's experimental activity, unfortunately.



(a) (b)

Figure 5. Simplified scheme of the transportable test loop (a); Absorber module, thermocouple placement and air mixer before the inlet tube sheet of the heat exchanger (b).

Therefore, additional high-temperature tests have been performed at the Synlight facility [7] at DLR (thanks to SFERA-III framework) with one single absorber module (≈ 14 x 14 cm of aperture) [8]. A tailored transportable thermal loop has been designed and constructed (Fig. 5 and 6). A simple scheme of the test loop is shown in Fig 5 (a). 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 sample (1), the receiver pipe (2), the air/water heat exchanger (4) and the flow meter (5). The absorber sample (1) is irradiated by concentrated light of several xenon lamps (7) with elliptical concentrators (8) [7]. The heat exchanger and the receiver unit are insulated (3) in order to keep thermal losses negligible.

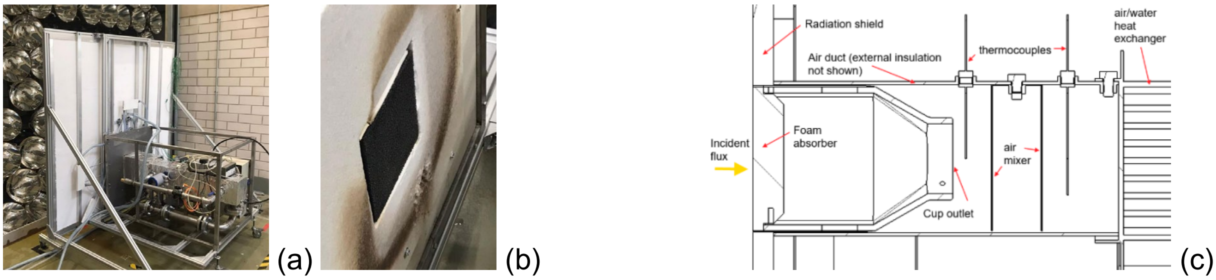


Figure 6. Test loop installed at the Synlight facility (a); Absorber and radiation shield after testing (b); Detailed view of the receiver air channel with mounted absorber module (c) [8].

Table 1. Measurement points obtained at the Synlight facility (P1 to P4).

Measurement point number	**Ambient air temperature (°C)**	**Outlet air temperature (°C)**	**Incident mean flux (kW/m^2)**	**Air mass flow (g/s)**
P1	31.4	913.5	975.7	16.1
P2	33.9	725.8	732.5	15.3
P3	34.8	766.5	541.5	10.8
P4	28.5	680.8	541.5	12.7

Table 2. Thermal efficiency of the CAPTure OVAR (absorber depth = 30 mm, cell diameter = 1.122 mm, strut thickness = 0.195 mm, porosity = 0.87, $\boldsymbol{\alpha}$ = 0.9, $\boldsymbol{\varepsilon}$ = 0.8, DNI = 1000 W/m^2).

Concentration ratio C (-)	**Receiver air outlet temperature (°C)**						
	400	**500**	**600**	**700**	**800**	**900**	**1000**
	η_r (-)	η_r (-)	η_r (-)	η_r (-)	η_r (-)	η_r (-)	η_r (-)
500	0.874	0.862	0.849	0.832	0.811	0.785	0.754
1000	0.880	0.872	0.862	0.852	0.840	0.826	0.810

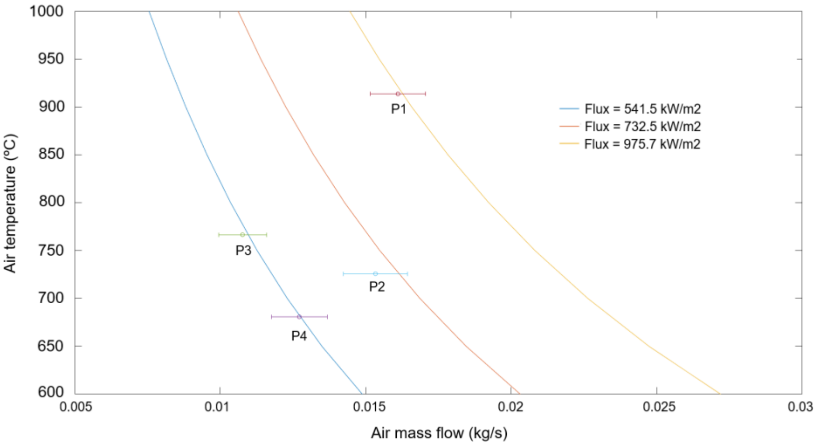


Figure 7. Comparison of numerical simulation results (solid lines) and experimental data (P1 to P4 with corresponding uncertainty ranges) [8].

Table 1 and Figure 7 display the experimental data (P1 to P4) and its comparison with numerical simulation results (using a Modelica 1-D absorber model as described in Ref. [9]) for three different levels of incident flux (≈ 975.7 kW/m^2, 732.5 kW/m^2, and 541.5 kW/m^2). As can be seen in Figure 7, theoretical and experimental data agree very well. Table 2 displays the expected solar receiver efficiency as function of air outlet temperature and flux level.

4 CAPTure OVAR application – CSP as well as process heat

The CAPTure OVAR technology is not only suitable for electricity generation in a CSP plant, but there are also promising applications regarding high-temperature process heat supply (up to about 1000 °C) in energy-intensive industries and solar fuels production. Furthermore, the proposed system is also able to be conveniently integrated with several technologies for energy storage, i.e. thermal (TES), thermochemical (TCES) [10] or compressed air energy storage (CAES) [11]. Concentrated solar thermal processing of minerals to produce metals has been shown to be technically feasible [12], however it has not yet been commercialized due to the high capital cost. The recent uncertainty and rise in fuel cost could however spark the integration of solar energy in this sector. Another possible sector of application is the cement industry, where the manufacturing process involves preheating-calcination at about 800-1000 °C. Finally, in the last decades, significant research has been conducted on the production of several potential fuels using air-based solar thermal energy, i.e. green hydrogen, easy-to-transport ammonia or syngas [13].

5 Conclusions

This work presents the CAPTure OVAR design that is based on ceramic stackable "*free floating*" absorber modules that form the receiver structure and avoid a complex metallic double membrane design. The new approach considerable simplifies the design and reduces receiver costs. Furthermore, the upscaling is simple. Nevertheless, the maximum stackable column height must be considered, which is defined by mounting limitations and material compression strength. Considering this, the design concept may only be suitable for small to medium-scale receivers up to about 50 MW thermal, which would fit well for the CAPTure concept [1] or other innovative plant configurations for distributed generation [11], as well as high-temperature process heat supply.

Data availability statement

All data supporting this article can be accessed in Refs. [1, 6, 8].

Author contributions

Fritz Zaversky: Conceptualization, Investigation, Methodology, Funding acquisition, Supervision, Writing – original draft; Xabier Randez: Investigation, Validation; Javier Baigorri: Investigation, Validation, Writing – review & editing; Marcelino Sánchez: Supervision, Review; Antonio Ávila-Marín: Investigation, Validation, Review; Jesús Fernández-Reche: Investigation, Validation; Alexander Füssel: Investigation, Review.

Competing interests

The authors declare no competing interests.

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