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Closed Solar Thermal Receiver for Air at Ambient Pressure

Concept and Basic Design with First Manufacturing and Testing

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Abstract. The concept for a closed solar thermal receiver for air at ambient pressure integrates robust heat storage with solids for concentrated solar power plants. The scalable modular receiver design features large internal surface areas for an efficient heat transfer and provides cavity effects to recover externally reflected radiation and heat. A competitive thermal efficiency was preliminarily calculated for the receiver design. The simulations of receivers with 2 MW and 150 MW thermal output indicate that the velocities of the heat transfer fluid and the temperatures of the receiver components remain in manageable magnitudes. The manufacturability of a fine cooling structure with thousands of cooling pins inside the ceramic receiver cap is demonstrated. Black coating of the outer receiver cap surface significantly increases the absorption of solar radiation. First tests for a single receiver module indicate feasibility of the concept. Further tests will be carried out and a pilot plant is to be prepared.

Keywords: Solar Thermal Receiver, Heat Transfer Fluid Air, Solid Storage System

1. Introduction

A variety of approaches exists for the configuration of concentrated solar power (CSP) plants. However, there is still a lack of a concept that is so universal, robust, and at the same time cost-effective that it can be used on an industrial scale. Such an industrial concept should achieve dispatchable contributions of solar heat and power supply on a scale comparable to power generation from fluctuating photovoltaics and wind energy.

In the "SolarRetrofit" project, an industrial concept for solar thermal power generation is being developed to application maturity. The concept integrates heat storage with solids, air at ambient pressure as heat transfer fluid, and a closed receiver that contains no transparent components. To this end, that new type of receiver concept is being developed, tested, and implemented and a solar thermal extension to an existing fossil fuel plant at a sunny location is to be prepared.

The "SolarRetrofit" project is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Project partner is the Institute of Solar Research at the German Aerospace Center (DLR) in Germany.

2. Thermal storage concept

A robust CSP configuration for universal usage in desert regions should meet several basic requirements. For example, a robust system must transition to a safe state if the external power supply fails completely. Since molten salt systems freeze at temperatures below 230 °C, their universal usage is questionable. For storing large amounts of solar heat, a robust and cost-effective alternative are solid systems, e.g., with bricks, rocks, or steel slag, being charged and discharged with pressure-free air as heat transfer fluid.

3. Receiver concept

It is reasonable to heat the air for a solid storage system directly in the solar receiver of a tower configuration. For use in harsh desert regions, a solar receiver must be robust against contamination from the environment. For this reason, a solar receiver should be sealed off from the environment at its hot end. Such receiver should also not contain any transparent components, because they can get dirty and overheat at these places. This leads to the concept of a closed solar thermal receiver for air at ambient pressure. Such concept is advantageous in comparison to existing open volumetric solar receivers for air for several reasons:

- Higher thermal efficiency since air can get recirculated completely and its remaining heat is not lost.
- Higher system efficiency since the operating pressure can be increased up to the pressure vessel limit.
- Greater robustness since no debris can penetrate through the receiver and clog air channels within the heat transfer system.
- Greater application flexibility since the air blower can be placed upstream at the cold end of the receiver. Instead, with an open volumetric receiver, the air blower can only be placed downstream of the heat consumer.

4. Design and numerical calculations of receiver

The described receiver concept requires competitive thermal efficiency together with reasonable pressure loss. This is achieved through an advanced modular design, which features large internal receiver surfaces for an effective heat transfer, and which provides cavity effects for regaining externally reflected radiation and emitted heat.

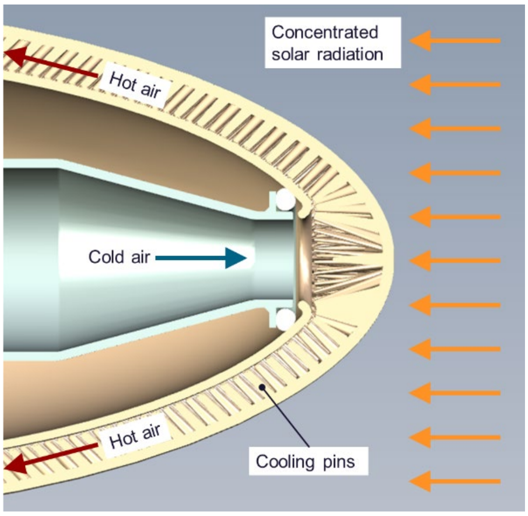

Figure 1. Tip of receiver segment with air channels and cooling pins

4.1 Basic design features of receiver

Radiation losses increase with a power of four of the absolute temperature. Thus, for getting high receiver efficiency, the solar radiation absorbing surfaces need to be cooled as much as possible. Specifically, this is necessary for the module tip where no cavity effect exists, and heat is being reflected to ambient. Therefore, in the receiver concept, the cold air is first led to the inner module tip as shown in Figure 1, providing there its best cooling performance.

The inner passage of the receiver segment is equipped with numerous cooling pins. This results in a large inner heat transferring surface area and allows for efficiently heating up the air flow to the desired temperatures while passing through a receiver module.

On its further path through the receiver module, the air heats up, which reduces its cooling performance and results in higher temperatures at the adjacent outer module surfaces. As shown in Figure 2, in a full receiver the individual modules are arranged in a tight array. Thus, heat emitted from hot outer module surfaces reaches neighboring modules and is not lost, which is the cavity effect. In addition, convection losses get reduced by the rippled outside receiver shape.

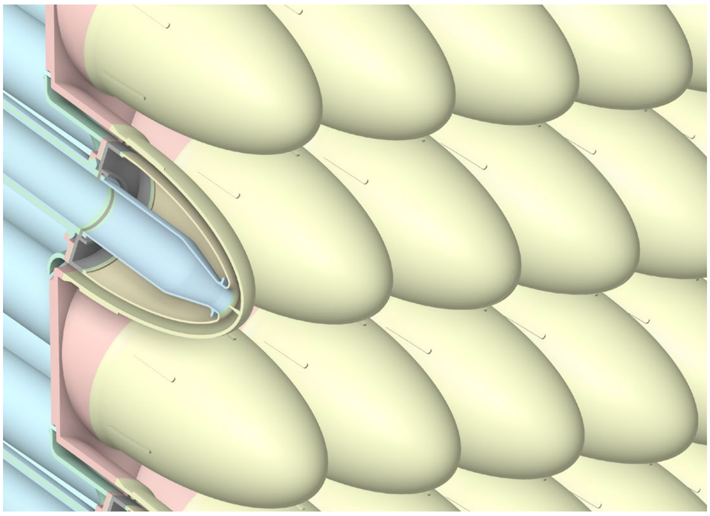

Figure 2. Allocation of receiver segments (inner cooling pins not shown)

These basic design features for reaching high thermal efficiency have been explored by Garbrecht et al. [1, 2], not for air as heat transfer fluid but for a molten salt receiver.

4.2 Performance data and materials of single receiver module

For the time being, the size of an individual receiver module has been designed for a thermal output of approx. 40 kW. The concentrated solar irradiation is 800 kW/m², which coincides with a typical heat flux for molten salt receivers. Larger external dimensions of modules are possible, with the optimum size being deducted from the manufacturability of the ceramic components. Herewith, hot solid components are predominantly made of SiC ceramic with high thermal conductivity and high temperature resistance, while cold solid components are made of steel.

For raising the temperature of the circulating air from 200 °C to 700 °C, a design point thermal efficiency of 90% has been preliminarily calculated for the closed air receiver by numerical simulations. This is the result of several optimizations of the design, where artificial intelligence has been used for the parallel adaptation of multiple design parameters.

Other concepts for solar thermal receivers with air at ambient pressure predict 87% design point thermal efficiency for 200 °C return air and 670 °C outlet air for an open volumetric receiver [3] or predict 85.73% design point thermal efficiency for 650 °C inlet air and 970 °C outlet air for a receiver where the solar radiation must pass through a transparent quartz window [4].

The mechanical design and the choice of materials allows for raising the receiver temperature to the limits of solid storage materials, i.e., starting from 650 °C with the option for raising up to 970 °C, a feeding temperature being described for a solar thermal system with solid storage and air as heat transfer fluid [5].

4.3 Calculation of receiver with 2 MW thermal power

The modular design makes it possible to increase the thermal output of a receiver by increasing the number of identical modules, which are connected in parallel to the ducts for cold air supply and hot air delivery.

A receiver with a thermal output of 2 MW consists of a total of 51 individual modules vertically arranged in 12 staggered rows and forming a circular segment with an opening angle of approx. 37 degrees. The heat flux and the temperature increase coincide with the data above for the single receiver module. Results of numerical calculations for a circumferential segment of a receiver of 2 MW thermal power are shown in Figure 3. These results indicate that the air velocities and the temperatures of the receiver components remain in manageable magnitudes.

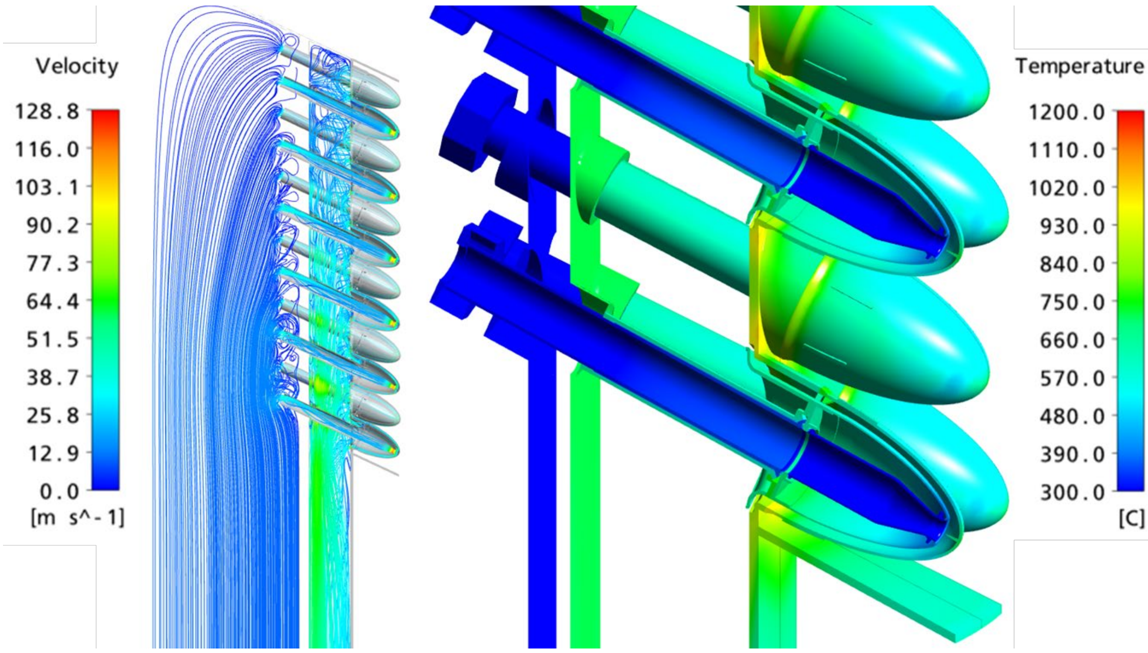

Figure 3. Flow velocities and surface temperatures in circumferential segment of receiver with 2 MW thermal power (inner cooling pins not shown).

4.4 Calculation of receiver with 150 MW thermal power

To verify the feasibility of the concept for larger solar thermal systems, a receiver with a thermal output of 150 MW was simulated. Such a receiver consists of 3800 almost identical individual modules, whereby the size of the modules has not yet been increased for this assessment. Figure 4 shows a front view, a sectional view, and an enlargement of a section of such a cylindrical receiver. The total height is 10 meters, the outer diameter is 8 meters, and the width of the ring-shaped hot air duct is 1.1 meters. The external dimensions are similar to the dimensions of molten salt receivers with comparable thermal power.

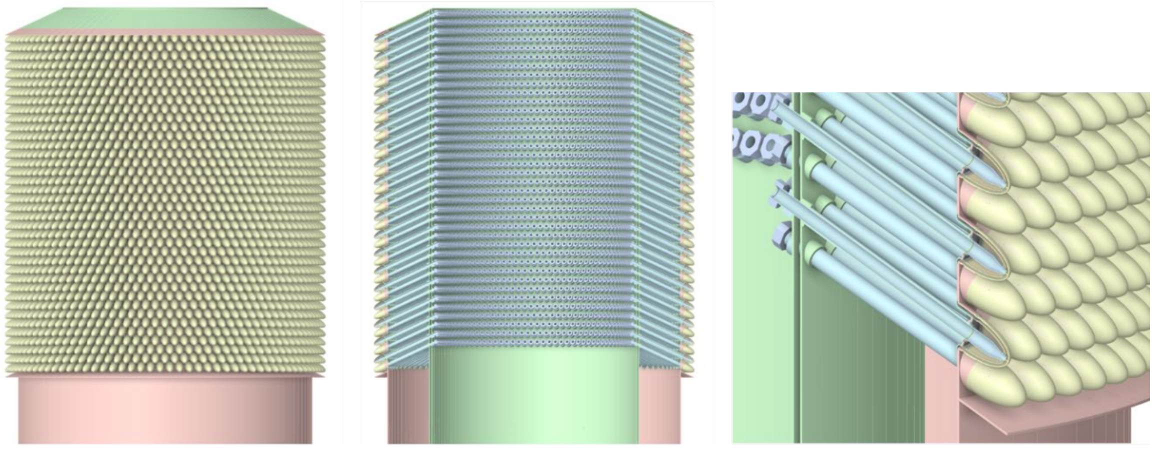

Figure 4. Views of receiver model with 150 MW thermal power.

The weight of a single receiver module is currently 25 kg, but it has not yet been reduced by design optimization. With a tentatively calculated weight of 137 tons for the 150 MW receiver, it is believed to be less than the weight of a 150 MW molten salt receiver in operation.

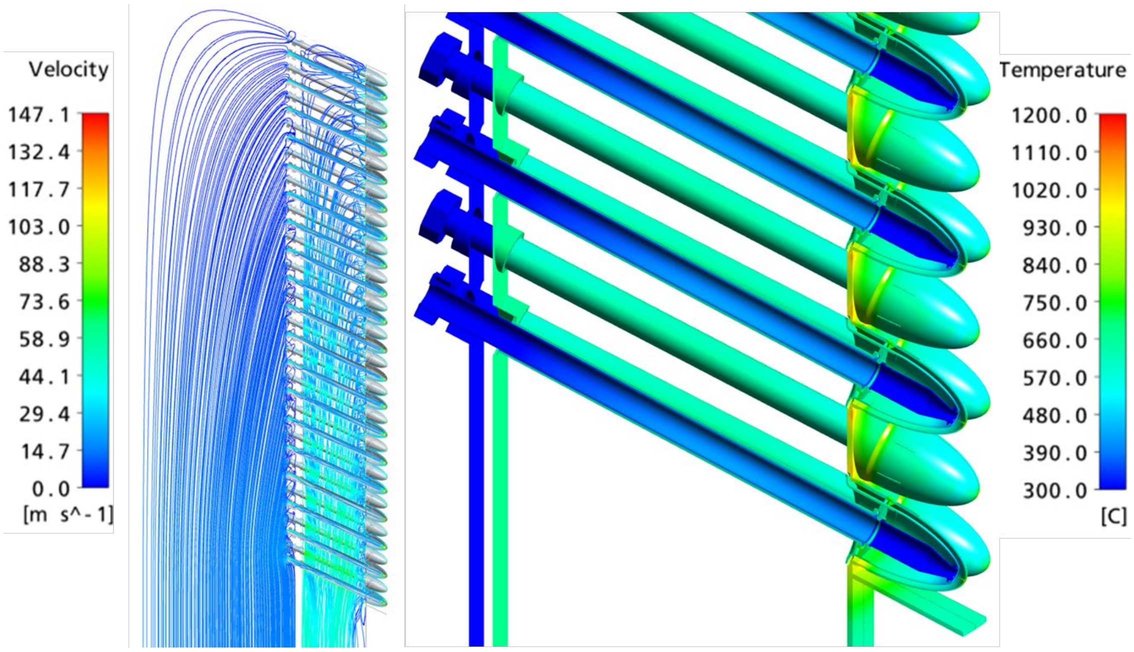

Figure 5. Flow velocities and surface temperatures in circumferential segment of receiver with 150 MW thermal power (inner cooling pins not shown).

Results of numerical calculations for a receiver of 150 MW thermal power are shown in Figure 5. These results indicate again that the air velocities and the temperatures of the receiver components remain in manageable magnitudes. A thermal efficiency of 90 % has been determined preliminarily, and the pressure loss of the receiver is provisionally calculated in the order of 150 mbar.

Therefore, the detailed results of extensive numerical calculations and optimizations of a single receiver module as well as multiple receiver modules indicate competitive efficiency combined with several conceptual advantages.

5. Manufacturing and coating of receiver modules

An important aspect of the receiver concept is the manufacturability of the fine cooling structure with thousands of cooling pins inside the ceramic receiver cap. The photo of Figure 6 shows such cooling pins and confirms the achievement with 3D printing of SiC ceramics.

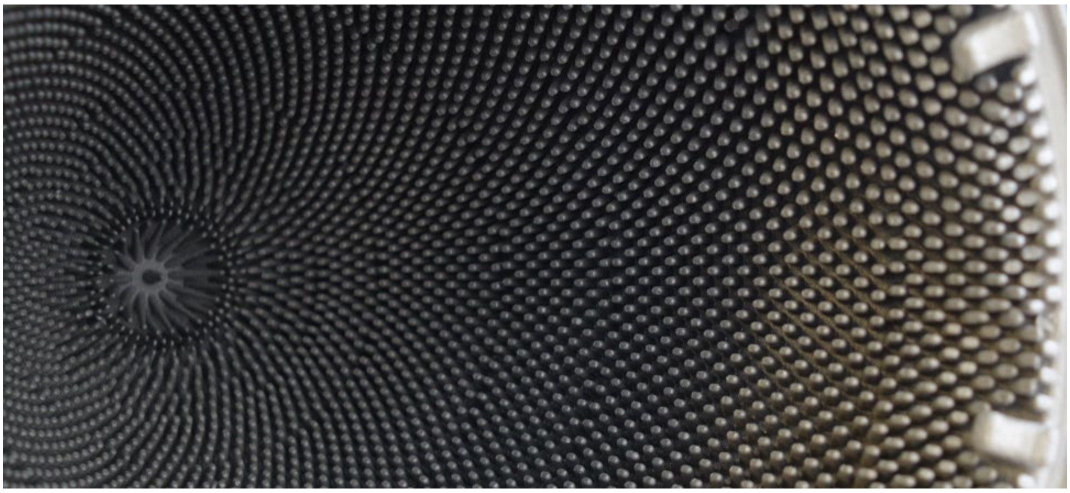

Figure 6. Inner surface of receiver cap with cooling pins.

Also, a complete receiver module was manufactured with 3D printed ceramics, several steel components and high temperature sealings.

In order to be suitable for 3D printing, the typically black SiC ceramic turns into a gray color. However, a black surface with a high absorption coefficient is crucial for solar thermal applications. Therefore, a receiver cap has been coated with Pyromark® 2500 [6] as shown in Figure 7.

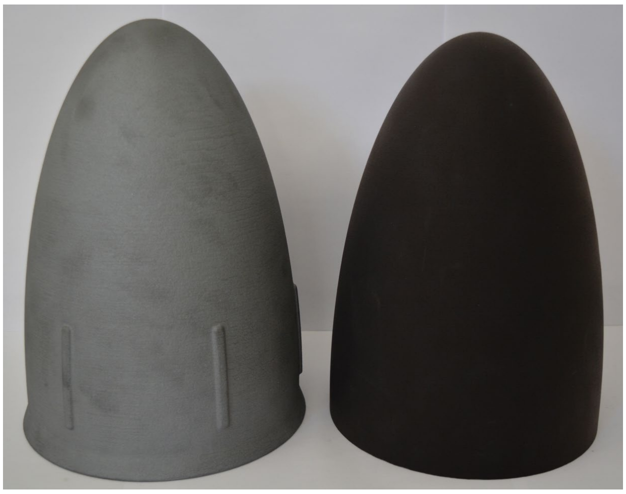

Figure 7. Ceramic receiver caps without coating and with Pyromark® 2500 coating.

The solar weighted hemispherical absorptance of the gray SiC is 0.856. Through the coating with Pyromark® 2500, that absorptance increases to 0.969. Both numbers have been determined by DLR at the Plataforma Solar de Almería, Tabernas, Spain (Sept. 2022, unpublished). Prior to receiving the real absorptance, an absorptance of 0.9 has been assumed for the numerical investigations of the receiver.

6. Testing of receiver modules

Siemens Energy in Mülheim/Ruhr, Germany, operates a test center for ceramic heat shields and other high-temperature components of gas turbines. Test stands are available with powerful heaters for near-infrared-irradiation. So far, two receiver modules were tested as shown in Figure 8 where the modules were shielded by insulation elements. Both, the receiver caps without coating and with black coating were exposed to high irradiation while cold air was being heated on its path through the receiver modules.

Figure 8. Receiver modules at test stand during assembly and operation.

Accurate pressure, temperature, and mass flow measurements were taken. No information is currently available for the radiated heat quantity. Against this background, quantitative results for the temperatures and the pressure loss as well as the following qualitative results are currently available:

- A peak temperature of 864 °C was measured at the tip of the receiver for the uncoated module and a peak temperature of 987°C for the coated module.
- Maximum outlet air temperatures of 620 °C were reached in both cases with an inlet temperature of 26 °C.
- The 3D-printed ceramic components and the steel components remained intact.
- The Pyromark® 2500 coating showed no delamination after the cooldown.
- In a cold air test, i.e., without radiative heating, the comparison of calculated and measured pressure losses for different mass flows matches with high accuracy.

The next step for testing at Siemens Energy in Mülheim/Ruhr will be the determination of the irradiated power reaching the surface of the receiver module. Then it will be possible to compare the results of numerical calculations and measurements regarding the thermal efficiency of the receiver module.

7. Outlook

For the “SolarRetrofit” project the outlook is as follows:

- A cluster of seven receiver modules will be tested under 310 kW_{rad} Xenon irradiation power at the Synlight facility of the DLR in Jülich, Germany. The Xenon-lamps emit a sunlight-like spectrum for realistic absorption values.
- A receiver test with a thermal output of 1 MW is being considered for the test platform of the solar tower in Jülich.
- The publicly funded R&D project “SolarRetrofit” also includes the preparation of a pilot plant, where thermal storage shall be integrated and where fossil fuel will be replaced partly by solar thermal heat in the range of 2-5 MW thermal. The site for the first pilot plant is not yet finally determined.

Data availability statement

The data for this work can be provided on request.

Author contributions

Ulrich Hueck: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Project administration, Supervision, Writing – original draft, Writing – review & editing. Wolfgang Haslinger: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – review & editing. Benjamin Raabe: Investigation, Methodology, Resources, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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Figure 9. Public funding for “SolarRetrofit”.

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