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VoCoRec - a Novel Two-Stage Volumetric Conical Receiver

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Abstract. At solar tower systems, open volumetric air receivers are attractive for electricity generation as well as for chemical and other industrial processes. In order to overcome inherent limitations within the previous lines of development, a fundamentally new receiver concept has been developed – the VoCoRec. It is characterized by a conical cavity with hexagonal cross-section, a two-stage air heating and modularity. Several simulations have been performed. For 800 °C hot air temperature, a total receiver efficiency of 88 % has been calculated, which is regarded very promising. A prototype receiver module with approx. 175 kW thermal output has been designed for the first tests in the solar simulator Synlight. The next step will be to manufacture the prototype. The tests in Synlight are scheduled to start in December 2021.

INTRODUCTION

At solar tower systems, open volumetric air receivers are an alternative to the presently prevailing molten salt and steam receivers. Open volumetric receivers provide a number of advantages. They are technically less complex than molten salt systems and offer the possibility of simple integration of heat storage, in contrast to steam receivers. Open volumetric receivers feature generally good robustness during transient operation and higher upper process temperatures (> 650 °C) than the currently dominant molten salt and steam receiver systems. Hence, they are attractive not only for electricity generation but also for chemical and other industrial processes. Air as heat transfer fluid comes with the benefits of being cost-free, infinitely available, non-toxic and without temperature limits. The remaining challenges with open volumetric receivers include - depending on the specific design - thermal efficiency, durability of absorber material and specific costs. [1]

The HiTRec open volumetric receiver design was developed in the 1990s and 2000s by DLR and CIEMAT [1] [2]. Figure 1 (a) illustrates the basic structural concept with an example of three modules, each with about 15 cm edge length. This design has been built up to a demonstration power plant, the Juelich Solar Tower with 1.5 MW_{el}.

In recent years, further improvements have been made to this receiver concept including a change to a cavity design, see Fig. 1 (b) [3] [4]. This aims at increasing the air return ratio (ARR) and decreasing radiation losses for higher receiver efficiencies. However, there remain inherent challenges, including limited hot air temperatures, complex piping and a high cooling demand for the support structure. Therefore, a fundamentally new concept has been developed – the volumetric conical receiver VoCoRec.

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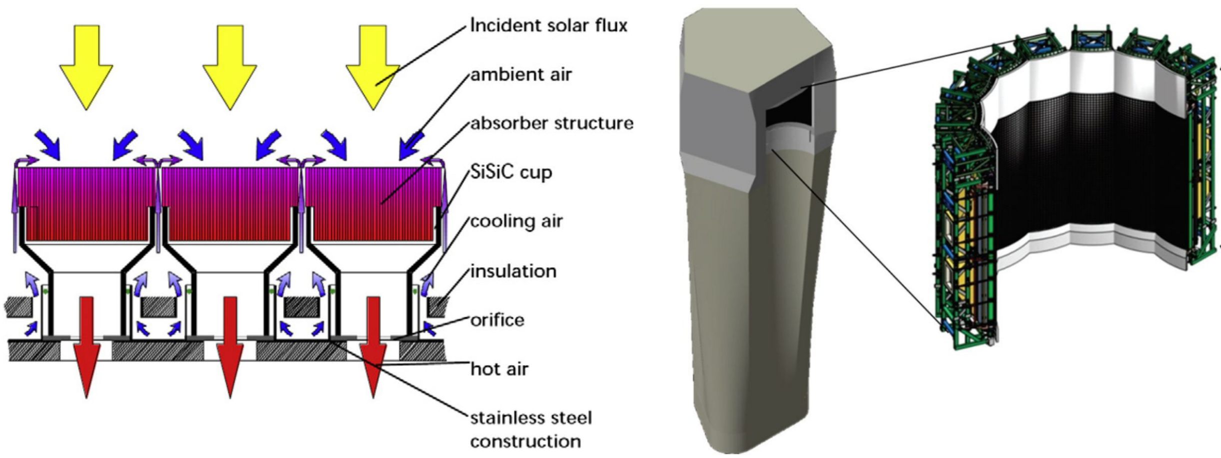
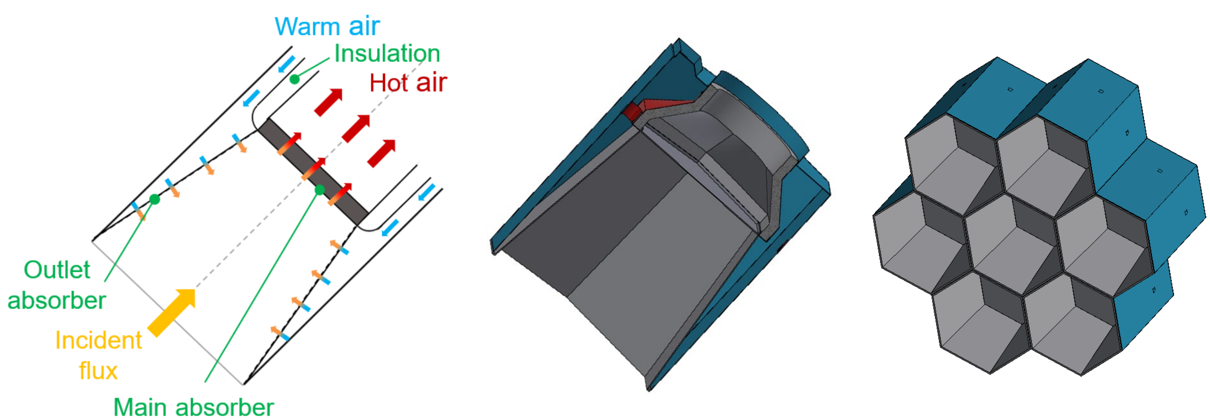


(a) (b)

FIGURE 1. (a) Scheme of HiTRec receiver design, three absorber modules shown [1].
(b) Improved HiTRec cavity receiver design [3]

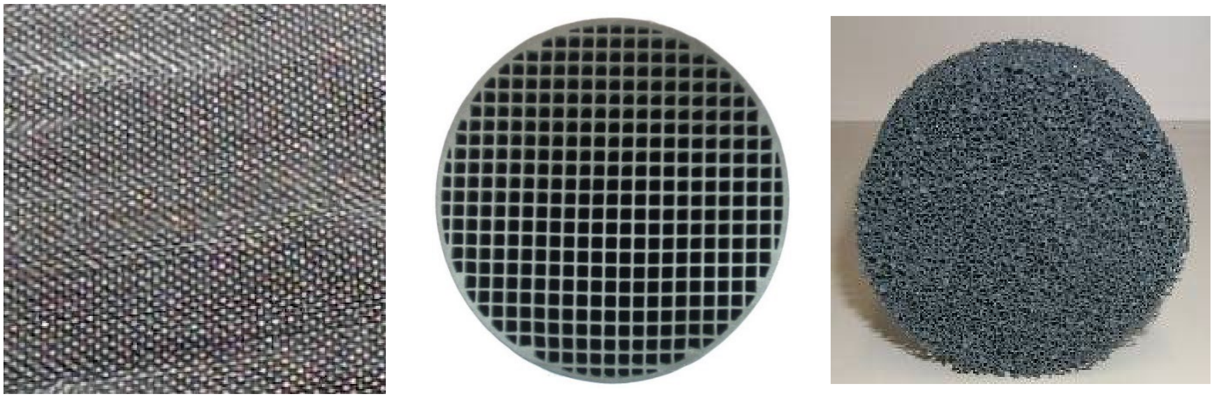
DESIGN FEATURES

Figure 2 illustrates the basic design of the VoCoRec. It is a modular receiver concept, where each module is an open cavity with a conical inner shape and a hexagonal cross-section. The air is heated in two stages. First, warm air with a temperature in the range of 100…200 °C flows into the cavity through an outlet absorber made of metal wire mesh while being heated up. In a second step, the preheated air is sucked through the main absorber made of metal wire mesh or ceramic structures (honeycombs, foams). Here, the air is heated to its final temperature of approx. 700...800 °C. Examples of the possible absorber materials are shown in Fig. 3. Module aperture width well suitable for production is expected to be in the approximate range from 400 to 1600 mm. The entire receiver can be formed as a cluster with an almost freely selectable number of modules.



(a) (b) (c)

FIGURE 2. VoCoRec basic design: (a) sketch of module, (b) CAD-model of module, (c) cluster of modules



(a) (b) (c)

FIGURE 3. Absorber materials: (a) metal wire mesh, (b) ceramic honeycomb, (c) ceramic foam

The design is made to achieve in different ways the main objectives of low heat generation costs and high hot air temperatures. This includes high thermal efficiency and low specific costs. In this context, the following advantages can be highlighted. The cavity geometry provides a high air return ratio and low radiation losses in comparison to external receivers. The two-stage heating also contributes to low radiation losses and favors high air temperatures. The achievement of high temperatures is additionally supported by a well-isolated separation of hot and warm air. The cooling requirement of the support structure is relatively low. The use of metal wire mesh as absorber material lowers the specific investment costs.

PERFORMANCE SIMULATION

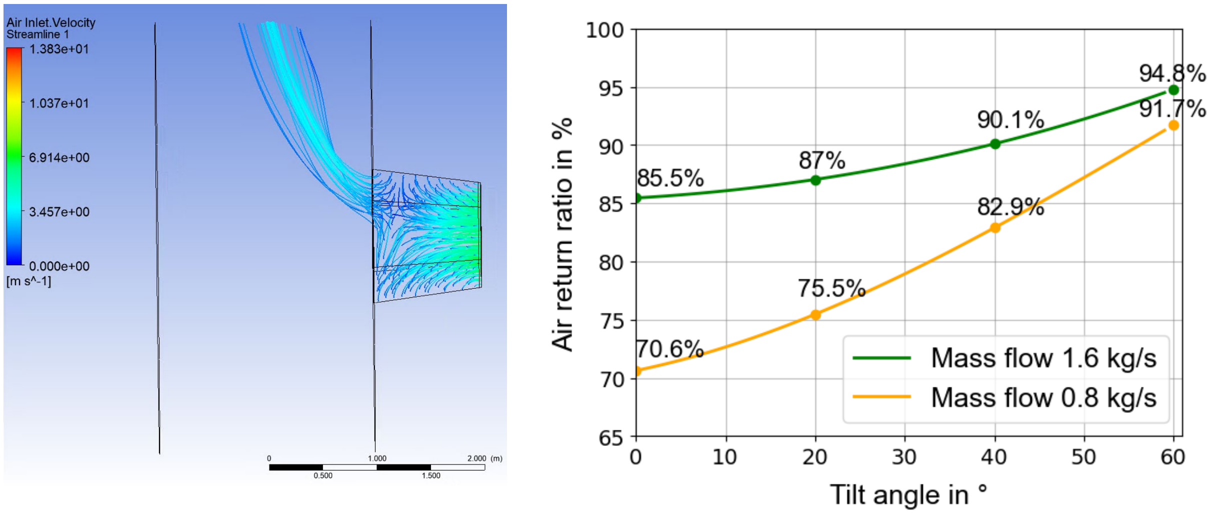
Various models were created and simulations performed to fine-tune the design of the first prototype. As a first step, the flux density distribution was calculated using the DLR in-house raytracing software SPRAY. By coupling raytracing with the absorber's geometry, the flux density distribution on the absorber surface was determined. The raytracing was performed for irradiation of the test rig in the solar simulator Synlight.

Air Return Ratio (ARR)

The air return ratio (ARR) has been examined closely. As the air circuit is open, not 100 % of the emitted air is sucked in again. A certain amount of warm air is lost and replaced by ambient air. The streamlines in Fig. 4 (a) illustrate the partial loss of warm air into the ambience. The ARR is defined as the ratio of the amount of emitted air, which is sucked in again, to the entire amount of warm air which is returned to the receiver. A high ARR contributes to high receiver efficiencies as with rising ARR values the reused part of the warm air's enthalpy rises, too.

CFD-simulations were carried out in order to determine the ARR for different receiver configurations (absorber geometry, operating case, tilt angle, number of modules). In Fig. 4 (b) the ARR's dependences on the tilt angle as well as on the mass flow is shown for an absorber module with 1074 mm aperture width. It is comprehensible that the ARR increases with rising tilt angles, because at a high tilt angle the air is prevented from escaping into the environment. This is especially true for buoyant warm air. The ARR also increases with rising mass flow. This can be explained by the relations between forced convection and natural convection. Natural convection is a driving force for air losses into the environment. As the mass flow increases, forced convection dominates over natural convection, causing the ARR to increase.

For the development of the first receiver prototype, the ARR of a single horizontal module with 470 mm aperture width under full load was calculated to be in the range 88…90 % for several design options.



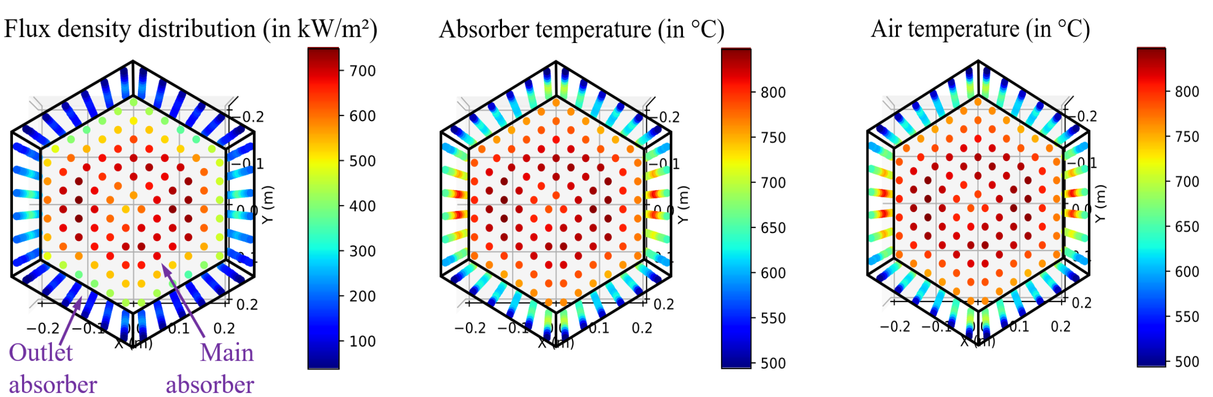
(a) (b)

FIGURE 4. Exemplary CFD simulation results for an absorber module with 1074 mm aperture width: (a) streamlines and air velocity for tilt angle 0°, (b) ARR over tilt angle (facing downwards) for full load (1.6 kg/s) and part load (0.8 kg/s), 0° tilt angle equals horizontal alignment

Temperatures and Efficiency

The DLR in-house code "Voreco" has been employed for thermal simulations. Voreco is a Fortran code which solves a differential equation system for heat transfer and air flow in order to simulate volumetric air receivers with regular 3D geometries. The input values comprise absorber geometry, flux density distribution, optical and thermal absorber properties, inlet air temperature, pressure and air return ratio. The code evaluates the radiation exchange problem in the cavity with the enclosure method, while the absorber structures are treated one-dimensionally. The results include absorber temperature distribution, outlet air temperature, air mass flow and receiver efficiency.

The outlet absorber and the main absorber made of metal wire mesh were divided into a total of 540 elements for the thermal simulations. Exemplary distributions of flux density, absorber temperature and air temperature are shown in Fig. 5. The flux density distribution was calculated for a spotlight setup in Synlight with a maximum angle of incidence into the aperture of 36°. In Fig. 5 (b) it is clearly visible that the outlet absorber temperatures are well below the main absorber temperatures which leads to lower radiation losses compared to a constant absorber temperature. Subsequently, the temperatures of absorber and air were used to calculate the temperatures and strains of selected structural elements.



(a) (b) (c)

FIGURE 5. (a) Flux density distribution, (b) absorber temperature and (c) air temperature for 470 mm aperture width, 1 MW/m² flux density in aperture plane and 800 °C hot air. Viewing direction perpendicular into aperture plane.

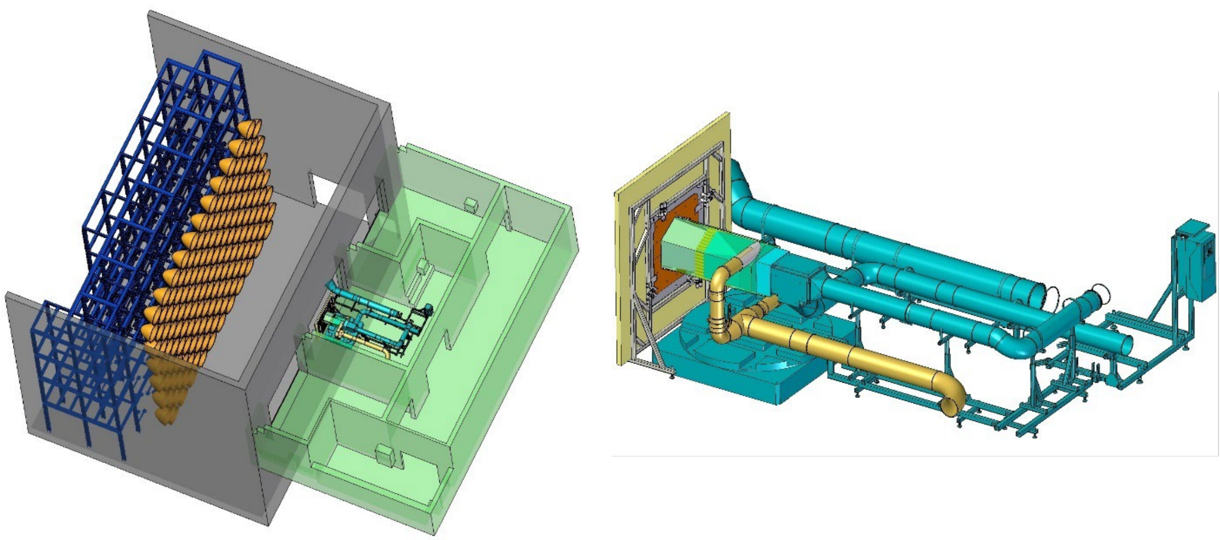
For a single horizontal module with 470 mm aperture width, 1 MW/m² flux density in the aperture plane and 800 °C hot air temperature, the simulations led to an overall receiver efficiency of about 88 %. This result is considered to be very promising for this temperature range. For comparison, the HitRec receiver achieves about 71% receiver efficiency as external receiver and 85% as cavity at 670 °C hot air temperature [4]. This shows a significant advantage of the VoCoRec design.

PROTOTYPE LAYOUT

The first experimental testing of the VoCoRec receiver concept will take place at DLR's Synlight, the world's largest artificial sun. The Synlight high-flux solar simulator comprises 149 Xenon-lamps with a maximum overall radiative power of 310 kW.

For the tests in the Synlight, a prototype VoCoRec receiver has been designed. It consists of a single receiver module whose geometry was chosen based on constructive boundary conditions as well as based on performance simulation results. The absorber will have 470 mm aperture width, 440 mm length and 4,3 ° opening angle. The design of the whole test rig is shown in Fig. 6 and Fig. 7. In the section view of Fig. 7 with the airway plotted, the key design features out of Fig. 2 can be seen again. After leaving the receiver, the hot air is mixed with ambient air in order to lower the air temperature for the protection of the blower. Figures 6 and 7 also show how the receiver's aperture plane is embedded in a water-cooled radiation shield. The nickel-based alloy Inconel 600 will be used for the metal wire mesh absorbers. A microporous insulation material has been chosen for thermal separation of hot and warm air.

The flux density in the aperture plane will reach up to 1 MW/m² during the tests. The thermal receiver output will be approx. 175 kW. It is intended to reach up to 800 °C hot air temperature. The tests are scheduled to start in December 2021.



(a) (b)

FIGURE 6. CAD model of solar simulator Synlight with VoCoRec test rig: (a) Total view, (b) close-up view of test rig (blowers not shown)

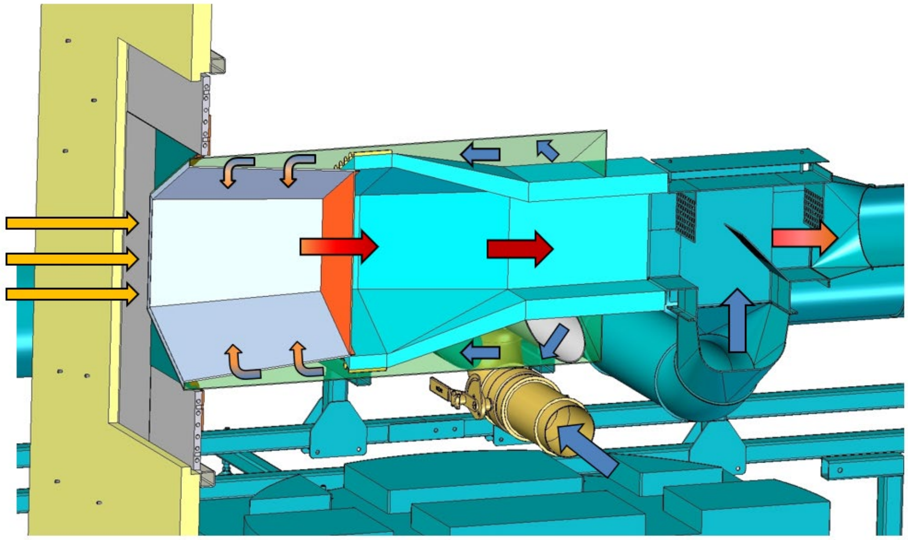


FIGURE 7. Longitudinal section view of test rig with irradiation (yellow arrows) and path of airflow

CONCLUSION AND OUTLOOK

In order to boost the development of open volumetric receivers, the VoCoRec receiver concept has been created. It is characterized by a conical cavity with hexagonal cross-section, a two-stage air heating and modularity. Several simulations have been performed in order to calculate the flux density distribution, ARR, absorber and air temperatures and receiver efficiency. The influences of mass flow and tilt angle on the ARR were studied. Simulated ARR values for a single horizontal module under full load are in the range 88…90 %. For 800 °C hot air temperature a total receiver efficiency of 88 % has been calculated for a single horizontal module. This is regarded very promising. A prototype receiver module with approx. 175 kW thermal output has been designed for the first tests in the solar simulator Synlight. The module will be 440 mm long and have an aperture width of 470 mm.

The next step will be to manufacture the prototype. The tests in Synlight are scheduled to start in December 2021. Temperatures and receiver efficiency will be measured and compared to simulation results. After successful testing of the first prototype, the next steps will comprise a scale-up with clustering several modules and an increase of hot air temperature. This is planned to be demonstrated at the Juelich Solar Tower. One focus will be on cooling and protecting the thin front surfaces of the receiver modules as well as the gaps between the modules.

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