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VoCoRec

Design and Performance of the Two-Stage Volumetric Conical Receiver

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Abstract. Open volumetric air receivers in solar tower systems are attractive for electricity generation as well as for process heat in chemical and other industrial applications. From the experience of past development stages, a new receiver concept was created with a conical cavity, with hexagonal cross-section for the modularity and a two-stage air heating. Several simulations have been performed. A prototype receiver module with approx. 175 kW thermal output has been manufactured and will be tested in DLR's Synlight. For different module sizes the cost estimation for industrial fabrication was calculated as well as the performance, ranging from 89% to 78% at 700°C hot air temperature.

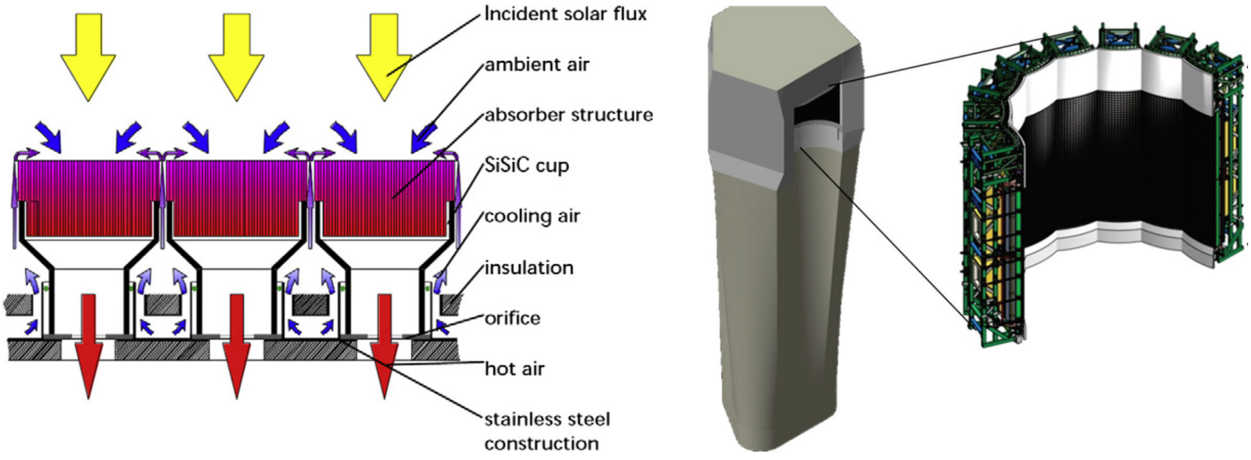
Keywords: CSP, Central Tower Receiver, Volumetric Air Receiver

1. Introduction

At solar tower systems, open volumetric receivers are an alternative to the currently prevailing molten salt and steam receivers. Air as a heat transfer medium has the advantage of being free, infinitely available, non-toxic and without temperature limits. Some of the advantages compared to steam systems are the possible integration of a storage device. Compared to molten salt systems, they are characterized by high robustness in transient operation and thanks to their higher possible process temperature of over 650°C, they are suitable for power generation as well as for various chemical and industrial processes. Remaining challenges with open volumetric receivers include - depending on the specific design - thermal efficiency, durability of the absorber material and specific costs. [1]

The HiTRec open volumetric receiver was developed by DLR and CIEMAT [1] [2] in the 1990s and 2000s. Fig. 1a) shows the structural concept using three modules as an example. The design was implemented in the form of a demonstration power plant at the Juelich solar tower with 1.5 MWel.

One disadvantage of this concept is the need for airflow to cool the support structure of the modules, illustrated by the blue arrows in Fig. 1a). By arranging the modules in a cavity (Fig. 1b)), not only the radiation losses are reduced, but also part of the blown-out air can be sucked in by the absorbers. Since this air has already heated up, the receiver efficiency increases with a higher air return ratio (ARR) [3] [4]. However, there are still problems such as limited hot air temperatures, complex piping and high cooling requirements for the support structure. Therefore, a fundamentally new concept was developed - the volumetric conical receiver VoCoRec.

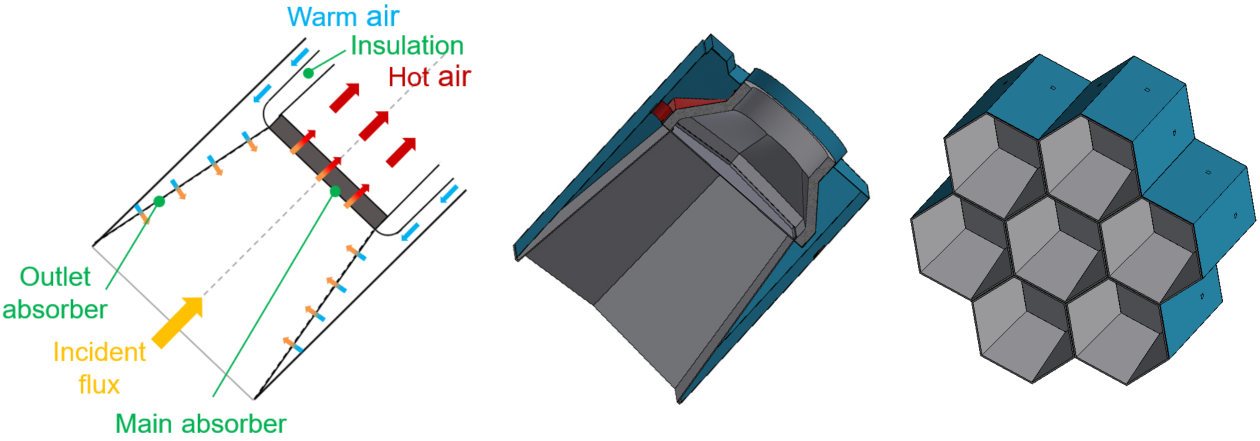


(a) (b)

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

2. 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 entire receiver can be formed as a cluster (Fig. 2c)) with an almost freely selectable number of modules. The solar-radiated absorber surfaces are made of several layers of metal wire mesh (Inconel) through which the air flows and is heated in two stages. In the first stage, the warm air with a temperature in the range of 100 °C flows through a radiated outlet absorber into the cavity. In the second stage, the preheated air is sucked through the main absorber. In this process, the air is heated up to its final temperature of approx. 700...800 °C.



(a) (b) (c)

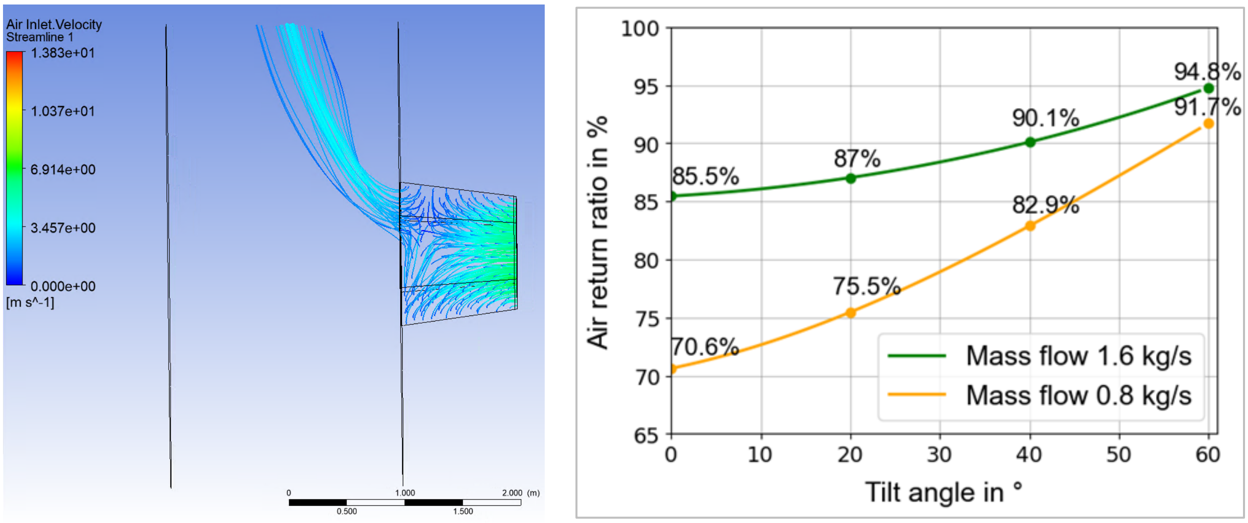
Figure 2. VoCoRec basic design: (a) sketch of module, (b) CAD-model of module, (c) cluster of 7 modules.

The layout supports the main goals of low heat generation costs and high hot air temperatures through a simple design structure with low specific costs and a high thermal efficiency. In this context, the following advantages can be highlighted. The cavity geometry ensures high ARR and low radiation losses compared to external receivers. The two-stage heating also contributes to low radiation losses due to the lower material temperature. The achievement of high temperatures is additionally supported by a well-insulated separation of hot and warm air. The cooling requirement of the supporting structure is relatively low. The use of metal wire mesh as absorber material lowers the specific investment costs.

3. Air return ratio and Cluster

The air return ratio (ARR) was examined in detail with the use of CFD simulations. Since the air circuit is open, not all of the exhausted air is sucked back in. A certain amount is lost after the first heating stage and is replaced by ambient air, the buoyancy of the hot air is due to its lower density. The streamlines in Fig. 3 (a) illustrate the partial loss of hot air to the environment. The ARR is defined as the percentage of exhausted air that is then sucked back in. A high ARR value contributes to a high efficiency of the receiver, because with increasing ARR values the reused part of the enthalpy of the warm air also increases. To investigate this, a stationary 3D Ansys CFX model was developed with SST turbulence settings. For validation, the mesh study was performed, which showed converging results.

The ARR was determined for different receiver configurations (absorber geometry, operating case, tilt angle, number of modules). Fig. 3 (b) shows the dependencies of the ARR on the angle of tilt and on the mass flow for an absorber module with an opening width of 1074 mm. It is understandable that the ARR increases with increasing tilt angle, since at high tilt angles the air is more strongly prevented from leaving the cavity by the buoyancy effect. The ARR also increases with increasing mass flow. This can be explained by the relations between forced convection and natural convection. Natural convection is a driving force for air losses to the surroundings. With increasing mass flow, forced convection dominates over natural convection, causing the ARR to increase.



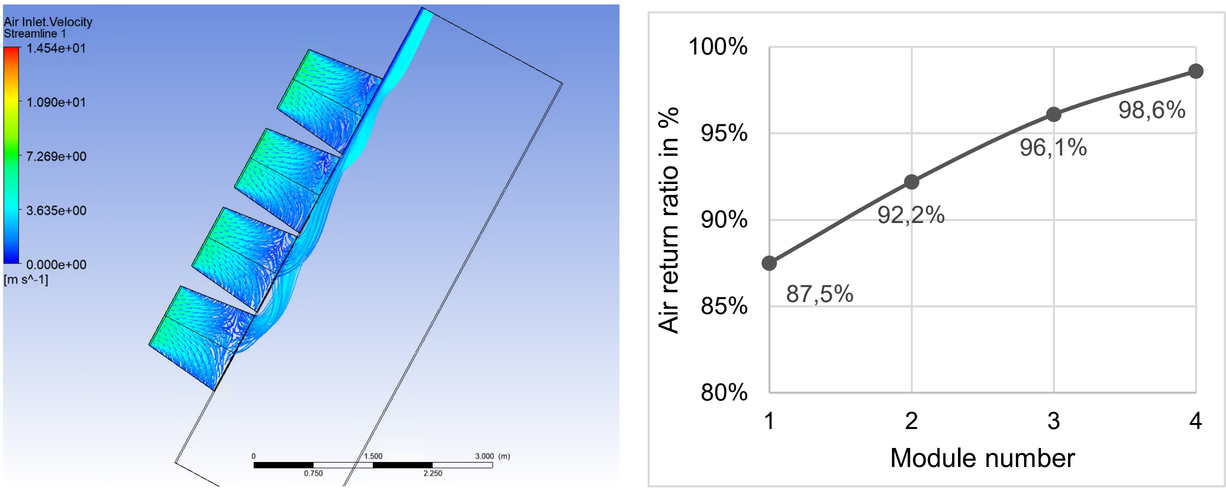
(a) (b)

Figure 3. Exemplary CFD simulation results for an absorber module with 1074 mm aperture width: (a) streamlines and air velocity for tilt angle 0° and mass flow 1,6 kg/s, (b) ARR over tilt angle (facing downwards) for full load (1.6 kg/s) and part load (0.8 kg/s).

An increasing effect for ARR is created by arranging several modules in the cluster, especially if the receiver is tilted. Fig 4 a) shows a CFD-model with four receivers arranged one above the other. The inclination is 25° and corresponds to the main incidence direction of the radiation at the main receiver in Juelich, which is also approximately the case for most tower systems.

In Fig 4 b) the results of the different modules are described; the calculation was done under full load (1.6 kg/s) and with an air temperature of 500°C after the first heating stage. The ARR increases significantly towards the top, as the preheated air escaping upwards due to natural convection is partially drawn in by the receiver above.

In order to achieve a conservative result for the receiver efficiency, the ARR of the lowest receiver was used in the further models, not least because no wind influences were considered.



(a) (b)

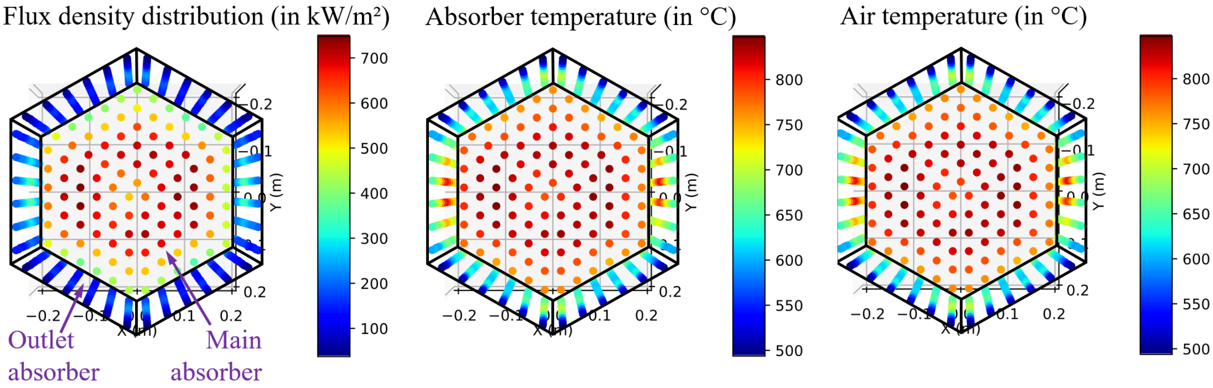
Figure 4. (a) CFD simulation results for four overlaying modules with 25° tilt angle and full load (1,6kg/s) (b) ARR of the four modules from bottom (module nr.1) to top (module nr. 4).

4. 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 Monte-Carlo-raytracing software SPRAY. By projecting the raytracing with the absorber's geometry, the flux density distribution on the absorber surface was determined.

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 ARR from the CFD calculation. 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.



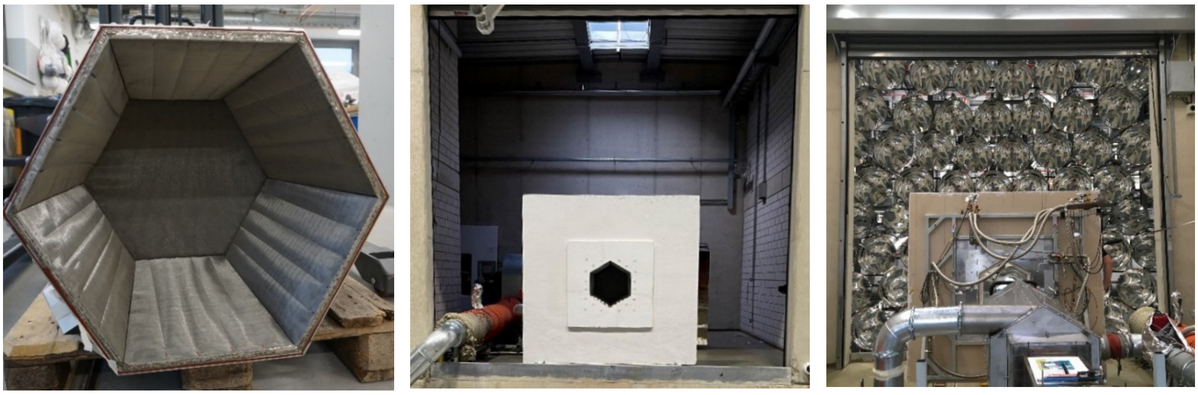
(a) (b) (c)

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.

5. Prototype Layout

In order to prove the design under realistic conditions, tests are foreseen at DLR's Synlight. With the help of the above-mentioned models, the geometry of a module of the VoCoRec concept was optimized and constructed with a design intercept power of 175 kW (1 MW/m² flux density in the aperture plane) and an outlet temperature of 800 °C. The aperture width is 473 mm, the length is 440 mm. The opening angle between the lateral receiver planes and the middle axis is 4,3° and the tilt angle of the receiver is 0°. The total absorber surface area (main and lateral absorber) sums up to 0.816 m².



(a) (b) (c)

Figure 6. Prototype of VoCoRec module with 473mm aperture width (a) view inside receiver aperture (b) receiver module built in test bench (c) view from test chamber towards lamps.

6. Module Size

Based on the layout of the prototype module a cost estimation was made for the industrial fabrication of VoCoRec modules of different unit sizes in a market relevant number. As can be seen from the results in Table 1, there is a general decrease in specific costs with increasing size. The exception is a cost increase from size 2 to size 3, which is due to the standard size of the wire mesh used. Sizes 2 and 4 are the most promising in this calculation.

The entire previously mentioned simulation setup was used to evaluate the thermal performance of the different module sizes (Table 2). The ray tracing was carried out for the solar field Jülich, and the flux density decreased somewhat with the larger sizes. Nevertheless, the key changes brought along by the module size can be compared well. The air return ratio decreases with increasing aperture size due to increased buoyancy. Since the outlet temperature is a boundary condition, a reduced specific mass flow is obtained for larger sizes, leading to higher material temperatures and thus higher radiation losses. Accordingly, the thermal efficiency decreases with the size of the unit (Figure 7).

Table 1. Basic geometries and cost estimation for four different module unit sizes.

	Size 1	Size 2	Size 3	Size 4
Aperture area [m²]	0.131	0.526	1	2.296
length [mm]	380	726	1000	1516
Specific cost [€/m²]	33‘878	23‘708	25‘024	16‘638

Table 2. Thermal performance of four different module unit sizes.

	Size 1	Size 2	Size 3	Size 4
Solar power into aperture [kW]	128.1	519.7	930.1	2111.1
Air return ratio [%]	92.7	88.7	86.4	83.0
Flux density in aperture [MW/m²]	0.983	0.988	0.930	0.918
Air inlet temperature receiver [°C]	27	27	27	27
Air temperature after outlet absorber [°C]	556	580	593	614
Air outlet temperature receiver [°C]	700	700	700	700
Max. Absorber Temp. [°C]	893	901	903	922
Spec. mass flow [kg/m² s]	1.237	1.158	1.108	1.057
Optical Efficiency [%]	95,5	95,3	95,0	94,7
Thermal Efficiency [%]	88.6	85.4	83.6	81.1

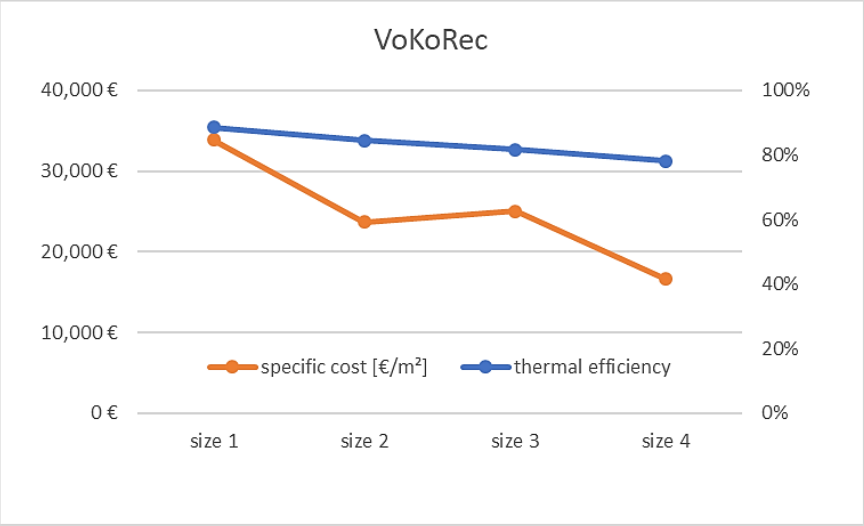


Figure 7. Specific cost and thermal efficiency of different module unit sizes.

A concept for the piping of the receiver modules in cluster arrangement was developed. Figure 8 shows the back view of a VoCoRec receiver cluster with warm air inlet in blue and hot air outlet in red. The air box with ducts for warm air is indicated in turquoise while the air box for the hot air is depicted in orange. The concept development for the cluster piping led to the conclusion that the specific cost of the air manifolds will increase drastically with decreasing receiver module unit size.

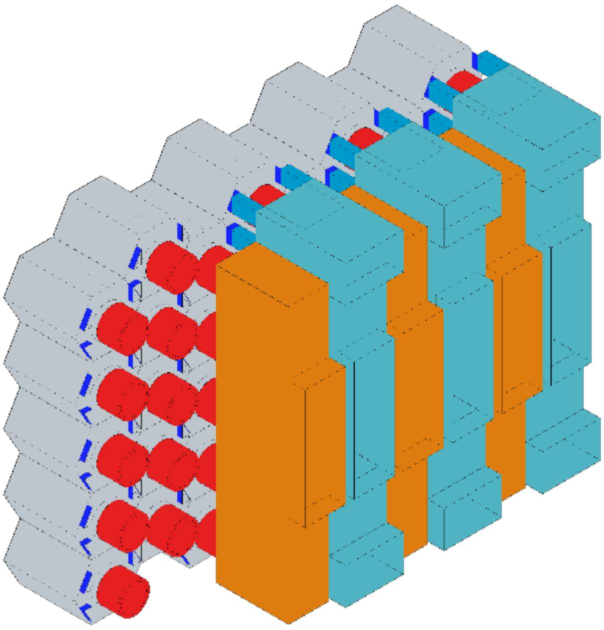


Figure 8. Concept for warm (blue and turquoise) and hot (orange and red) gas piping for VoCoRec receiver cluster.

7. 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. For the absorber with 0.5 m² at 700°C outlet temperature and 25° tilt angle, an optical efficiency of 95% and a thermal efficiency of 85% were calculated for a flux density of 0.988 MW/m².

A prototype receiver module with approx. 175 kW thermal output has been designed for the first tests in DLR's solar simulator Synlight. The module will be 440 mm long and have an aperture width of 470 mm. The prototype and the testbench have been manufactured.

The next steps will comprise a scale-up with clustering of several modules and an increase of hot air temperature. This is planned to be demonstrated at the Juelich Solar Tower. The influence of the wind has not been investigated so far. It could have a major influence on efficiency and should be considered. Another focus will be on cooling and overheat-protection of the thin front surfaces of the receiver modules as well as the gaps between the modules.

Data availability statement

Various numerical simulations (CFD, ray tracing) and a Fortran Code were used to generate the data presented in this paper. The data obtained is presented in graphics in the paper.

Underlying and related material

The receiver surface is made from 10 layers of metal wire mesh, a nickel-based alloy Inconel 600 (2.4816)

Author contributions

K. Busch: Supervision, Conceptualization, Methodology, Writing, Review & Editing; **R. Uhlig**: Methodology, Writing, Review & Editing; **P. Schwarzbözl** Supervision, Conceptualization, Writing, Review & Editing; **W. Schneider**: Methodology **S. Kolbe**: Methodology **T. Doerbeck** Conceptualization, Methodology, Review & Editing

Competing interests

“The authors declare no competing interests.”

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