Performance Assessment of an Improved Open Volumetric Receiver Design with 240 MW_{th}

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Abstract. Due to their proved robustness, good operating characteristics and the easy way to include thermal storage open volumetric receivers with air as heat transfer fluid are an interesting alternative for central receiver power plants. This alternative represents a significant step forward in plant availability and technical controllability to achieve the terminal goal of high probabilities and expectancy levels of annual electric yields representing the basis for the competitiveness and dissemination of dispatchable solar thermal systems. Though high availability has been shown in demanding transient and part load cases a permanent goal is to increase further efficiencies for future commercial scale receivers. In the current study a novel receiver design for a 240 MWth solar tower is presented which was optimised for reduced radiative losses and high air return ratios – a crucial parameter for obtaining high efficiencies of open volumetric receivers. With the help of a CFD model, which was recently specifically developed for the simulation of open volumetric receivers, the performance of the new receiver design was assessed. Under design conditions of 670°C hot air and 270°C return air temperature the receiver efficiency based on the intercept on the absorber reaches 84.3% and the air return ratio reaches 84.8%. At reduced hot air temperature of 560°C the efficiency even exceeds 90%.

INTRODUCTION

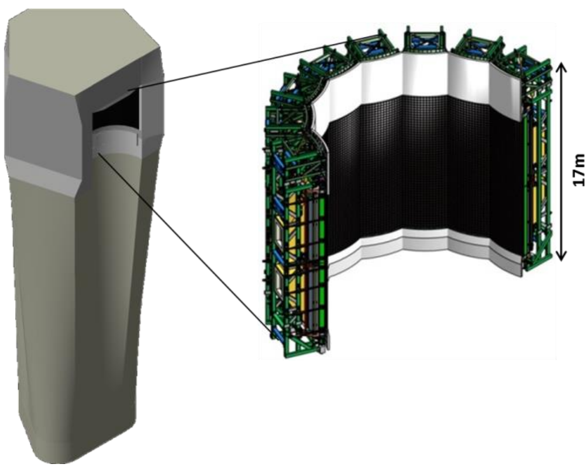
Central receiver power plants with open volumetric receiver are an alternative to the currently deployed salt or steam receivers. Their advantage compared to salt receivers is the relative technical simplicity as no heat tracing and no drainage during night-time is required and the heat transfer fluid cannot be overheated. The advantage compared to steam receivers is the option to easily integrate a heat storage system. A complete solar power plant with open volumetric receiver is being demonstrated with the Solar Tower Jülich in Germany since 2009. The robust receiver operates for more than 8 years now without damage or major incidents at highly volatile DNI conditions.

For commercial viability of a solar thermal technology both availability and average efficiency (dominant part load efficiency and peak efficiency at design conditions) are key success factors. The first target of proving availability of the open volumetric receiver and heat storage has successfully been shown at the Solar Tower Jülich. Increasing efficiencies while maintaining the very high availability levels has been the mission for this research project.

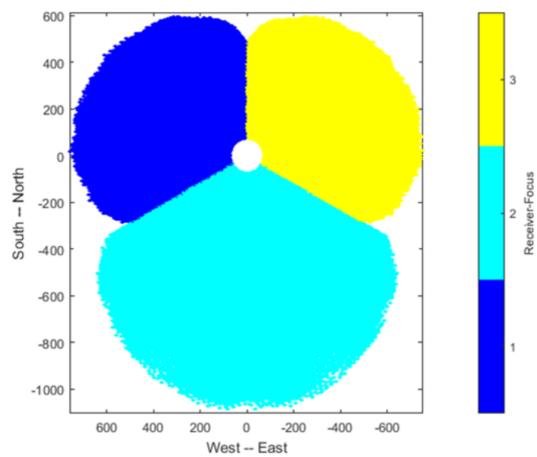
For the open volumetric receiver with ceramic absorber efficiencies of around 76% have been reported for a small scale system [1] and around 71% for the Solar Tower Jülich [2]. Recent investigations have highlighted the potential to increase the efficiency by optimising the air return system [3, 4]. Measurements with a newly developed measurement system [5] at the Solar Tower Jülich have shown air return ratios (ARR) in the range between 50% and 70% [4]. It was shown, that it is beneficial for the overall system performance to return parts of the warm air externally instead of using the entire stream for the cooling of the receiver.

DESIGN OF THE RECEIVER

Based on the extensive results obtained at the Solar Tower Jülich and on the studies mentioned above, a novel receiver design in cavity shape has been developed by the industrial research partner Kraftanlagen München. Moreover, the internal structure of the receiver has been improved compared to the state of the art in order to reduce thermal losses of the hot air and improve flexibility during start-up and transient operation to maintain overall plant availability. As shown in Fig. 1, three receivers are included in a solar tower concept designed for a 360° heliostat field with a total intercept power of ~285 MW. The orientation and the size of the individual receivers have been optimised with the raytracing software STRAL [6] resulting in a main receiver facing south with ~125 MW and two smaller receivers with ~80 MW each facing North-East and North-West (60° and 300°), respectively. In each receiver face the absorber is a concave cylinder with a defined opening angle. Each cavity is closed on top by a roof and is open to the bottom so that radiation from heliostats nearby the tower is not blocked. A part of the warm return air is blown out through the absorber surface and the rest is returned through an external air return system from below the absorber [4]. In the current investigation the efficiency map for the main receiver was evaluated.



(a)



(b)

FIGURE 1. Design of the improved three-face cavity receiver (a) and subdivision of the corresponding heliostat field (b).

CFD MODEL

For the estimation of the receiver performance a combined model has been developed [2] resolving the air flow in front of the receiver by means of CFD and taking into account the absorber behaviour by means of a characteristic map derived from a 1D-FEM model [8]. With this model, for the first time it became possible to consider both, the characteristics of the volumetric absorber and the air flow in front of the receiver. The detailed structure of the absorber consisting of an array of small rectangular absorber modules with narrows air return gaps in between is approximated by a surrogate structure which can be resolved with reasonable accuracy in the CFD model. On this surrogate the characteristic in- and outflow behaviour as well as the radiative properties are evaluated on basis of the 1D-FEM model. Compared to [2] where the model is described in detail, here, a revised characteristic map for the improved internal structure has been used.

Performance Evaluation

For the estimation of the receiver efficiency map simulations with varying temperature and load conditions have been carried out. The focus of the study presented here is on the design configuration of the main receiver face (design intercept of 125 MW, hot air temperature of 670°C and a return air temperature of 270°C) and part load conditions with the same temperature conditions. The effect of forced convective losses through wind was neglected here and will be analysed in detail in a follow-up study.

The high return air temperature of 270°C was chosen for combination with a high efficiency water steam cycle, but for an optimisation of the entire system a variation of the return air temperature (200°C and 110°C) was carried out as well. In addition, a case with a reduced hot air temperature (560°C) was investigated which might be an option at low part load conditions. In receiver part load the heat storage is not charged and the entire hot air is used for steam generation and turbine operation for which a lower temperature can still be used. In a real plant an overall optimisation including receiver and Rankine cycle performance and auxiliaries as the fan power will determine when it is favourable to decrease the hot air temperature.

Boundary Conditions and Simulation Models

On the absorber the newly developed boundary conditions for the velocity and the temperature of open volumetric receivers [2] was used. The irradiation on the absorber is increased by reflection of spillage from inner cavity walls as well as by emitted radiation from the absorber which partly hits other parts of the absorber. This effect is considered by simulating the radiative heat exchange via a view factor radiation model [7]. All faces in the cavity of the receiver are considered for the radiative heat exchange (names “absorber”, “absorber radiation shield”, “roof”, “ear radiation shield” in fig. 2) whereas radiation on the outside of the receiver is neglected in order to increase simulation efficiency.

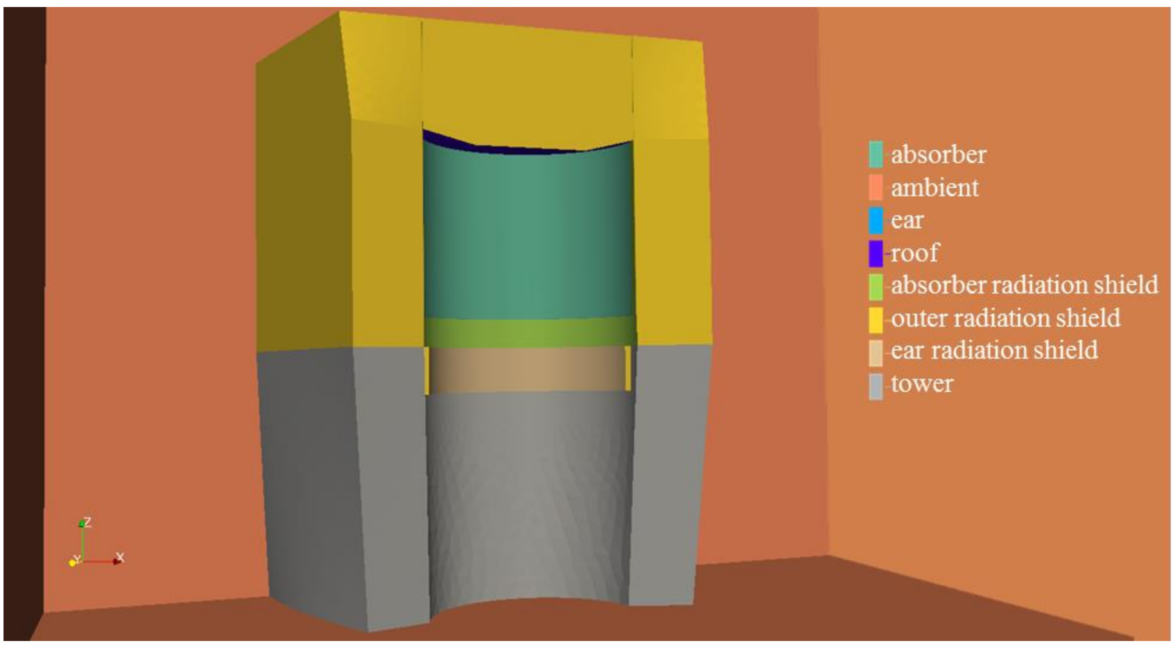


FIGURE 2. Receiver model for CFD simulations (patches with similar boundary conditions are shown in the same colour, ‘ear’: external air return).

Part load conditions are simulated by scaling of the design intercept distribution as would occur by reduced DNI. Thus, all load conditions are easily comparable and the trend over various load conditions becomes clear. Early morning or late evening intercept distributions can be simulated in addition to give an impression of the influence of skewed radiation distribution.

The return air is split into air going through the absorber (internal air return) and another part being ejected from below the receiver (external air return). The receiver is designed so that the internal fraction is fixed to 50% of the total design mass flow for cooling purposes. For part load conditions of 50% and less the entire return air is thus led through the absorber. In the simulations the fraction of the external air return was fixed to 50% at 100% load, 37.5% at 80% load, 16.7% at 60% load, and 0 % at and below 50 % load, respectively.

Efficiency Calculation

For external (flat or convex) receivers the efficiency of the receiver is usually determined by relating the useful power to the intercept on the absorber surface. In comparison, for cavity receivers the useful power is usually related to the intercept on the aperture. For the current design the first approach gives very high values for the receiver efficiency since part of the spillage from the inner cavity surfaces next to the absorber is also used. However, using the cavity definition for the efficiency is not expedient since the design is open to the bottom and thus has a very large aperture area compared to normal cavities. Nevertheless, the chosen definition of the efficiency does not alter the performance of the entire system, since high efficiency values according to the definition for external receivers coincide with low intercept factors from the heliostat field and vice versa. Thus, in the current study the efficiency will be calculated as the difference of the enthalpy flows of the hot air and the return air related to the intercept power on the absorber, eq. 1.

$$\eta = \frac{\dot{H}_{hot\,air} - \dot{H}_{return\,air}}{\dot{Q}_{intercept,absorber}} \qquad (1)$$

Mesh Independence Study

Four different mesh refinement levels ranging from 6.4 mio cells to 19.5 mio cells have been investigated prior to the parameter study presented here. All results are within a narrow band for both, the air return ratio ARR ($\pm 1.0\%$) and the efficiency η ($\pm 0.3\%$), see table 1. Similar to the results found for the simulation of the Solar Tower Jülich [2], the mesh independence study gives estimation for the discretisation error. For the subsequent simulations the mesh with 10.5 mio. grid elements was chosen so that a conservative estimation of the discretization error is about $\pm 0.5\%$. This finding was confirmed by a transient simulation on the coarsest mesh which did not show any substantial deviation from the steady-state solution.

TABLE 1. Results of mesh independence study (for hot air temperature of 650°C).

Mesh size	6.4 Mio	10.5 Mio	16.2 Mio	19.5 Mio	6.4 Mio transient
ARR	83.7 %	84.4 %	85.7 %	84.7 %	
η	86.9 %	87.1 %	87.4 %	87.2 %	87.0 %

RESULTS

Figure 3 shows the air return as a function of the total mass flow. The general trend which was observed at the Solar Tower Jülich [2, 4] can be seen here as well. However, it becomes apparent that the data follows two different forms of this trend: one at a lower level where the entire return air goes through the receiver ("ELR=0") and one with at a higher level where parts of it go through the external air return system ("ELR>0"). With external air return the air return ratio reaches about 85 % at design conditions (240 kg/s) with decreasing values at lower mass flows. Without external air return the air return ratio is about 4-6 %-points lower.

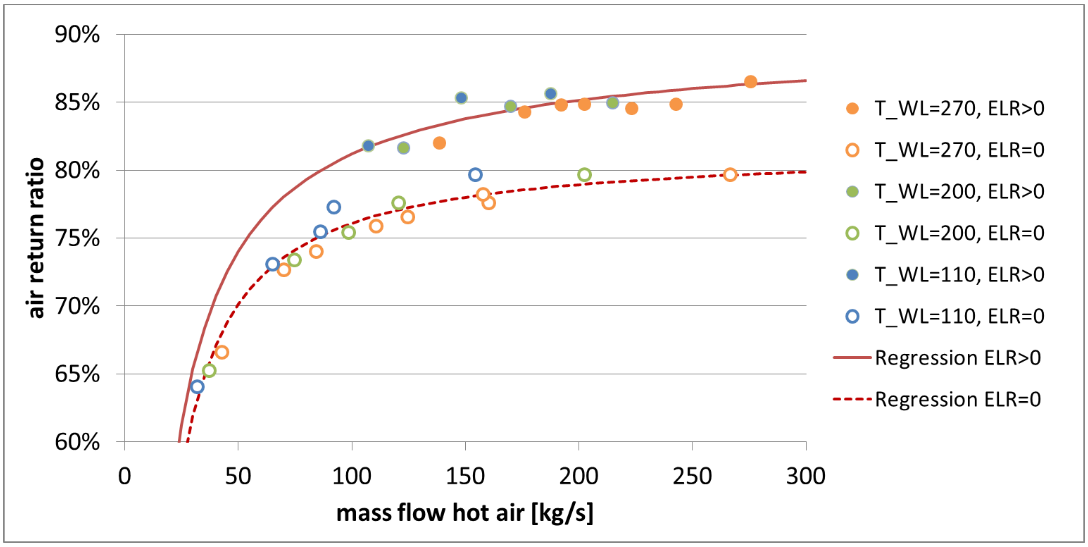


FIGURE 3. Air return ratio as a function of the receiver mass flow with ("ELR>0") and without ("ELR=0") external air return for varying return air temperatures ("T_WL").

Although low values of the mass flow have not been simulated with external air return system and the available data could also be fitted by a linear regression, the power law regression was still used for this data for the sake of consistency.

Figure 4 on the left shows the concentration of the return air in front of the absorber for a hot air temperature of 650°C at full load. As can be seen, over a wide range of the entire receiver area the air return ratio is close to 100% with lower values only in the upper third of the receiver and at the outer edges. On the right hand side the concentration of the return air is shown in three horizontal and one vertical section through the air volume inside the receiver cavity. It can be seen from these sections that the return air stays close to the absorber surface. It moves upwards due to the external air ejection and the natural convective draft. On its way up it mixes with ambient air so that it gets diluted and eventually moves forward at the roof of the receiver. There, the air leaving the receiver contains roughly 50% of return air.

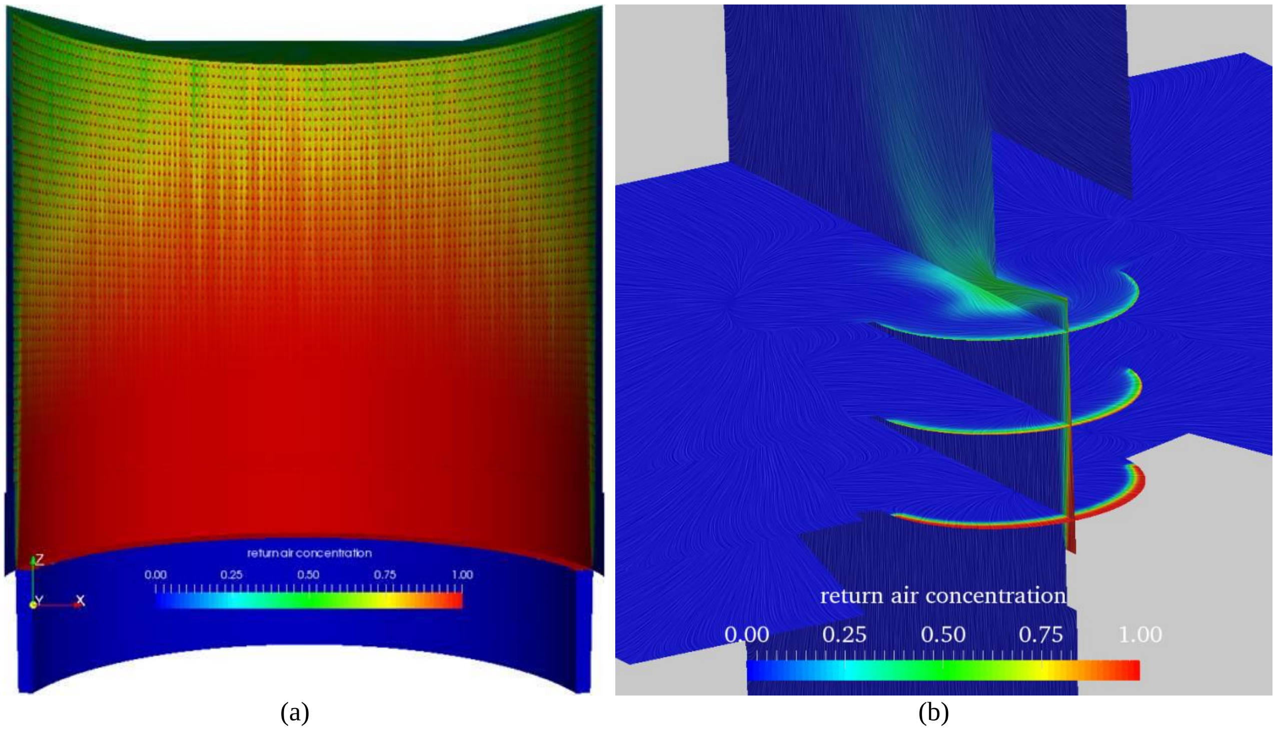


FIGURE 4. Concentration of the return air on the absorber front (a) and distribution of the return air in the receiver cavity as seen from inside the tower (b).

The receiver efficiency follows a similar trend as the air return ratio. In fig. 5 the receiver efficiency is plotted as a function of the load condition for two different hot air temperatures and three different return air temperatures. For the design intercept, a hot air temperature of 670°C and a return air temperature of 270°C, the efficiency reaches 84.3%. At part load conditions this efficiency drops to 76.9% at 50% load and 59.3% at 25% load. The reduction of the efficiency at part load conditions can primarily be attributed to radiative losses which are dominated by the hot air temperature and thus do not decrease significantly with the load.

A reduction of the return air temperature leads to an increase of the receiver efficiency. The main effect here is a reduced mass flow which, in combination with a basically constant air return ratio, leads to reduced convective losses. With a reduction of the return air temperature to 200°C, an efficiency of 87.0% can be reached and 89.7% at 110°C, respectively.

As mentioned above, a reduction of the hot air temperature can be an option to increase the efficiency, particularly under part load conditions. While this increase is between 1 and 3.5 %-points at design load, it is between 10 and 16 %-points at 25 % load. While the benefit at the high load conditions might as well be compensated by an increased power demand of the fans (a higher air mass flow is needed at the reduced hot air temperature), the reduction of the hot air temperature allows an efficient operation of the receiver also at low part load conditions.

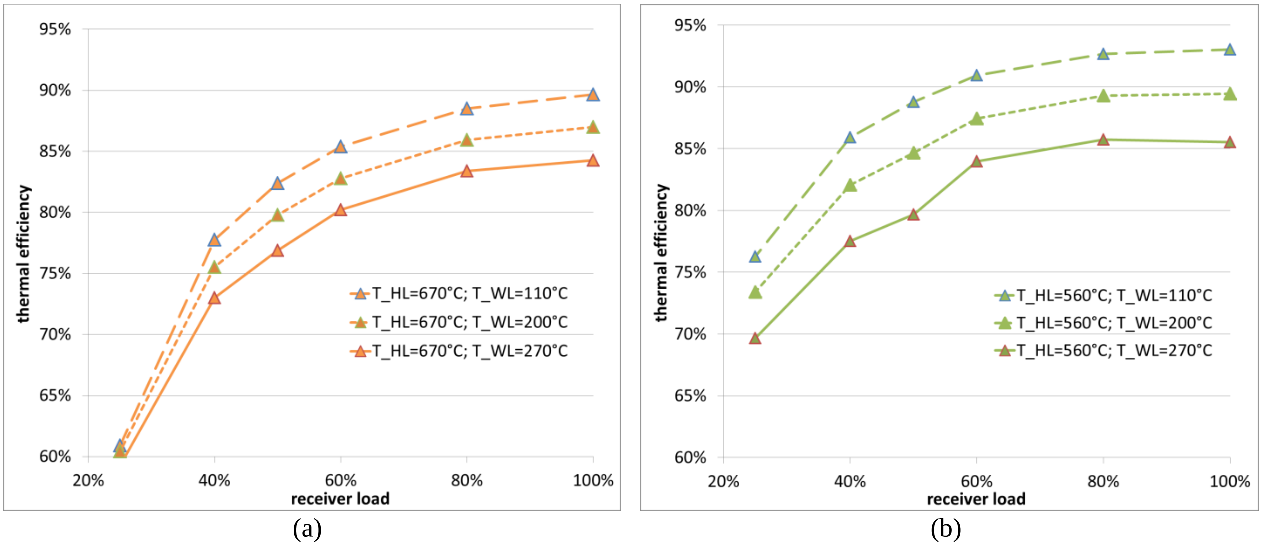


FIGURE 5. Receiver thermal efficiency as a function of receiver load for varying warm air temperatures: (a) for 670°C hot air temperature, (b) for 560°C hot air temperature.

Table 2 gives the values of the most important heat fluxes and the key parameters for five different operation points. The last column of this table (η_2) gives the efficiency as it is calculated when the entire radiation reaching the receiver aperture is used as reference as compared to only the radiation hitting the absorber (η_1) as defined by equation (1). The difference between both definitions is equivalent to the difference between the intercept on the absorber surface and the intercept on the aperture which is about 11%.

TABLE 2. Main receiver performance characteristics.

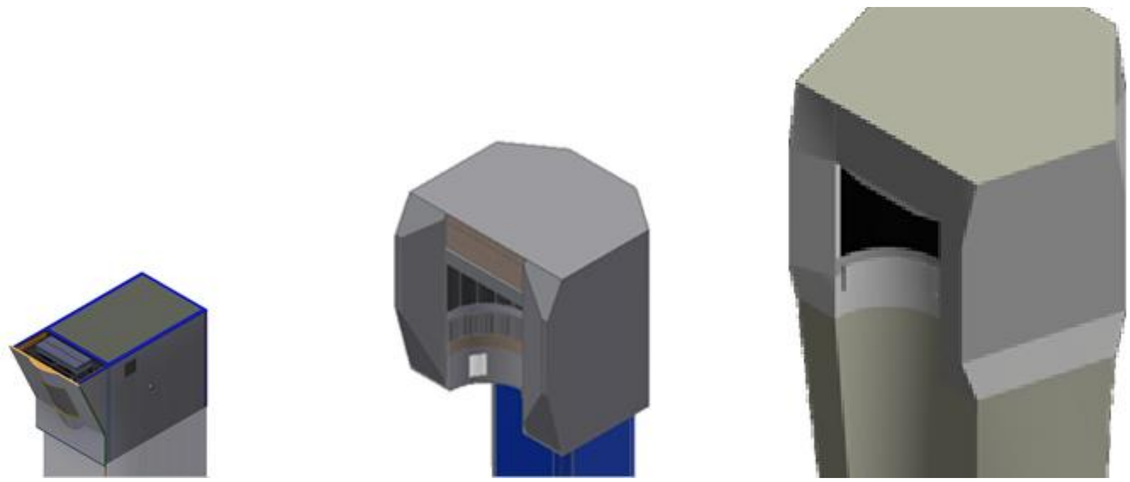
T_{hotair}	$T_{airreturn}$	$\dot{Q}_{int}$	$\dot{Q}_{spill}$	P_{air}	$\dot{Q}_{airloss}$	$\dot{Q}_{rad}$	ARR	η_1	η_2
670°C	110°C	125.2 MW	14.4 MW	112.2 MW	3.2 MW	19.7	85.7%	89.7%	80.4%
670°C	110°C	62.6 MW	7.2 MW	51.6 MW	3.1 MW	14.9 MW	75,4 %	82.4%	73.9%
670°C	270°C	125.2 MW	14.4 MW	105.5 MW	9.9 MW	19.1 MW	84.8%	84.3%	75.6%
560°C	110°C	125.2 MW	14.4 MW	116.5 MW	3.5 MW	12.9 MW	86.4%	93.0%	84.3%
560°C	200°C	62.6 MW	7.2 MW	53.0 MW	6.1 MW	8.2 MW	77.5 %	84.7 %	75.9 %

CONCLUSIONS AND OUTLOOK

In the new receiver design the air return ratio reaches values up to more than 85% and the thermal efficiency reaches values of almost 90% (at design hot air temperature of 670°C). Hence, compared to the state of the art receiver design at the Solar Tower Jülich the efficiency is increased by around 20%-points. These results improve dramatically the competitiveness of the open volumetric receiver concept compared to the salt or steam receivers being installed in small numbers commercially at the moment.

The potential for further improvement can now be evaluated with the simulation model. Among the parameters that will be investigated are the distribution of the hot air and the return air, the optimized ratio of the external air return, as well as the detailed part load behaviour. The influence of wind on the air return ratio and on the interaction between the individual receivers of the full solar tower will be investigated with a model of the entire solar tower in a follow-up research project.

The Jülich receiver with about 8 MW_{th} has to be scaled up by a factor of up to 30 to reach commercial viability depending on the local market regulation schemes. Based on the underlying theoretical and comprehensive findings such up-scaled receiver designs will be developed at the structural level in a following research project to ensure technical controllability and cost control while maintaining the determined performance results herein. In this respect, parallelly pursued commercial projects incorporating a one-face cavity receiver, which represents a single face of a large three-face receiver, will add further information to this development process with the objective to reach a scale addressing the main solar tower markets in the sun belt. As one example, at the moment a 10 MW_e plant project with a receiver of 70 MW_{th} is currently being developed near San Severo, Italy. Furthermore, projects are pursued in China requiring receiver scales of >240 MWth for the upcoming market framework of phase 2 which will follow phase 1 attracting demonstration projects only.



(a) (b) (c)

Figure 2. Scale-up steps of the open volumetric receiver: (a) Jülich 8 MW_{th}, (b) 70 MW_{th} one-face receiver and (c) 240 MW_{th} three-face receiver for a commercial 60 MW_{el} plant.

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