DIRECT ABSORPTION RECEIVERS FOR HIGH TEMPERATURES

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Abstract

Three concepts of direct absorption receivers for concentrating solar power (CSP) systems are compared. They are characterized by advantages like simple design, high working temperatures and good storage possibilities leading to a potential reduction of the levelized electricity costs. The design of the first concept, the liquid film receiver, is based on a face-down cylindrical barrel, whose inner surface is cooled by a directly irradiated molten salt film. Detailed investigations regarding film stability and system management strategies reveal increased receiver efficiency by implementing a slow rotation and inclined receiver walls. The second concept resembles the first one, but instead of molten salt small ceramic particles are used as heat transfer medium. The solar radiation is directly absorbed by a falling particle curtain whereas appropriate recirculation strategies of the particles can lead to high receiver efficiencies for all load conditions. While the above described systems are suitable for the 50 to 400 MW_{th} power range the third concept – also a particle receiver – can be applied in decentralized small-scale CSP plants ranging from 100 kW_{th} to 1 MW_{th} as well as in larger systems with up to 200 MW_{th}. Due to centrifugal acceleration the particles are forced against the cylindrical receiver wall where they form a thin layer which is directly heated up by incoming radiation. The particle retention time and with it the mass flow can be adjusted to all load conditions by regulating the rotation speed.

Heliostat field layout calculations for different design power levels were carried out comparing the annual performance and levelized cost of heat for a face-down receiver and a receiver with an optimized inclination angle. Only small differences between both concepts could be noticed. However, simplified assumptions regarding thermal receiver losses were made neglecting e.g. convection losses. Thus, in order to give reliable information about the thermal efficiency of the introduced concepts, computational models considering the main heat loss mechanisms are developed. The models are accompanied by experimental validation and support the numerical findings.

Keywords: concentrating solar power, direct absorption, high temperature, particle receiver, molten salt

1. Introduction

Investigations from the 1980s have shown that direct absorption receivers (DAR) have the ability to achieve higher outlet temperatures compared to conventional salt in tube receivers [1]. Higher heat losses due to higher temperatures can be overcompensated by gains from the power block efficiency leading to higher overall system efficiencies. Combined with lower receiver and system costs (e.g. parasitic losses < 1%) and the inherent feature to store the heat transfer media, reduced levelized electricity costs (LEC) seem achievable [1, 2]. Beside power generation, a broad band of other applications can be addressed with DAR systems, such as solar fuel or high temperature process heat applications.

One of the earliest works concerning DAR was published by Shaw et al. [3], where a continuously operating heat exchanger system is described. Different DAR concepts were intensively investigated by the Sandia National Laboratories (SNL). They studied the governing mechanisms of the liquid film and addressed important features of the solid particle receiver concept. Several experimental setups and computation models were developed to assess the critical aspects of the liquid film concept, which include stability of the cooling liquid salt film [4], influence of doping particles in the salt [5], the effect of roughness of the absorber surface on the heat transfer into the film [6] and the thermal expansion of the absorber structure. An assessment of the cost reduction potential related to the investment costs of the receiver [1] was also conducted.

The technical feasibility of a solid particle receiver was first shown by Hruby [7]. Her investigations focused mainly on the development of a receiver design and the selection of proper particle materials. Based on the assessment study by Falcone et al. [8], which indicated competitive costs of the solid particle receiver compared to the least expensive air receiver concepts for high temperature applications, the design of a free falling particle receiver was proposed. More work regarding flow characteristics and convective heat transfer in a falling particle curtain was studied experimentally and numerically [9], while Griffin et al. [10] conducted an extensive evaluation of proper materials with special attention on optical properties. Recently, SNL tested a prototype solid particle receiver on-sun [12], providing an experimental basis for the validation of numerical simulations. A computational fluid dynamic (CFD) model of the prototype developed by Ho et al. [13] which considered irradiation from the concentrated solar flux, two-band re-radiation and emission from the cavity, discrete-phase particle transport and heat transfer, gas-phase convection, wall conduction as well as radiative and convective heat losses showed good agreement with the experimental data with an average relative error of less than 10 %.

Currently, three different DAR concepts are under investigation at the DLR. Their basic design, functional principle and main advantages and challenges are introduced in the following sections. A schematic of a DAR combined with power block and storages is shown in Fig. 1. The main parts of the power plant are the receiver, the heat exchanger, a high and low temperature storage, the power block, a thermal process or thermo-chemical cycle (which is not shown in Fig. 1) and a transport system. Solar radiation is directly absorbed in the receiver by the heat transfer medium which can be either instantly used to drive a power block, a thermo-chemical cycle or other thermal processes via a heat exchanger or be stored in the high-temperature storage. After passing the heat exchanger the cooled down medium is kept in the low-temperature storage where it can be transported back to the receiver to be heated again.

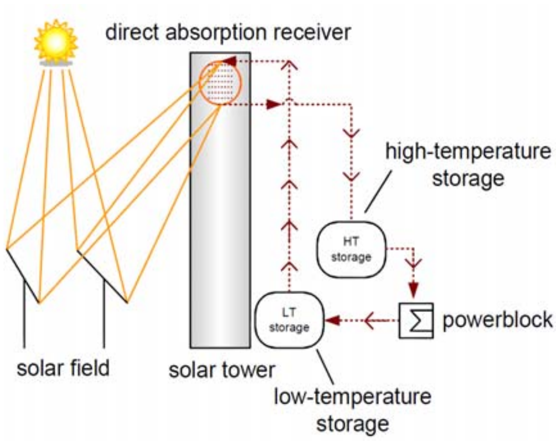

Fig. 1. Schematic of a DAR system with power block and storages

A further option is the multi-tower configuration, where a horizontal transport system, which could consist of a number of isolated containers, would transfer the heat transfer medium to a central heat storage and back.

2. Field efficiencies

The performance of a solar power plant is strongly dependent on its heliostat field efficiency and the receiver efficiency. For minimized convection losses and therefore maximum receiver efficiency a face-down configuration (90°) with a circular aperture would be a favourable angle. However, for best field efficiencies an ideal inclination angle can be calculated according to the selected assumptions. Thus, an optimized receiver inclination angle exists with the highest combined efficiency of the field and the receiver which will lie in between these two values.

In order to demonstrate the difference between these configurations, annual performance calculations were done using the DLR heliostat field layout tool HFLCAL [14]. Cost optimized field configurations are compared for plant sizes of 1 MW_{th} and 350 MW_{th} thermal receiver power at design point, each with an optimized inclination angle and a fixed angle of 90°. The cost assumptions for the considered cases are specified in Table 1.

Field (based on reflective area)	130 €/m²
Tower function* for case a and b	$19.428 \cdot T_H^{\ 2} - 84.01 \cdot T_H + 7483$, in €
Tower function for case c and d [15]	$C_T = 0.63 \cdot (600000 + 17.72 \cdot T_H^{\ 2.392})$, in €
Receiver (power specific)	50000 €/MW_{th}
O&M	2 %

*according to offer from Pfleiderer (July 2002)

Table 1. Cost assumption parameters used in HFLCAL

The design point is chosen to be solar noon on March 21st and the calculations are made for a site in Seville, Spain (37°23’N). Since the main objective of this investigation is focused on different heliostat fields constant receiver parameters for all cases are assumed: The optical efficiency is set to 97 % and the thermal loss density to 84 kW/m². Note that this is a simplified receiver model where only constant thermal radiation losses corresponding to an inlet temperature of 600° and an outlet temperature of 1000° C are considered. Convection losses are neglected. A detailed description of the methodology and all other assumptions can be found in [2]

Figure 2 shows heliostat field layouts for the four different cases. The colour chart on the left side of each field indicates the annual heliostat efficiency from about 80 % (green) to 60 % (red) including cosine losses, blocking and shading, atmospheric extinction and intercept losses. The installation of the face-down receiver on top of the tower is done in such a way (support ring or lamp configuration) that blocking losses due to mounting devices can be neglected.

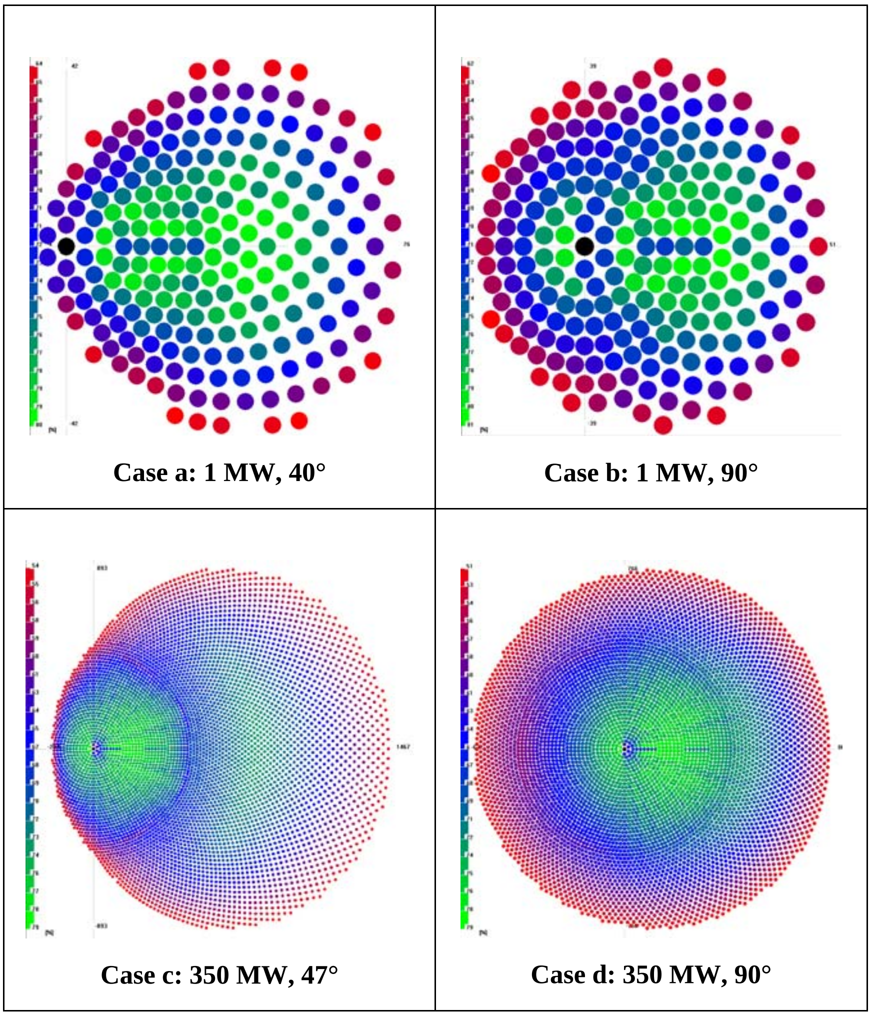

Fig. 2. Heliostat field layout for different systems

As expected, a significant number of heliostats from the south-field are included for the face-down configuration (case b and d) in contrast to the fields with an optimized receiver angle where basically heliostats from the north-field were used (case a and c). However, comparing the calculation results, listed in detail in Table 2, just minor differences regarding annual performances and the levelized heat costs can be noticed. Therefore, one can conclude, that a face-down receiver apparently does not have severe drawbacks on the heliostat field efficiency but exhibits important advantages for the receiver efficiency which will be clarified in the following sections. Note that the receiver efficiency shown in Table 2 is not representative for the actual efficiency since constant receiver parameters for all four cases were assumed for this study. In general, the face-down concept results in a little bit higher towers.

	1 MW, 40°	1 MW, 90°	350 MW, 47°	350 MW, 90°
Design power	1 MW_{th}	1 MW_{th}	350 MW_{th}	350 MW_{th}
Inclination angle	40°	90°	47°	90°
Heliostat area	8.24 m	8.24 m	121.33 m	121.33 m
Heliostat number	215	222	5607	5863
Tower height	31 m	37 m	290 m	327 m
Tower radius	2 m	2 m	15 m	15 m
Receiver radius	0.59 m	0.60 m	9.34 m	9.47 m
Annual receiver efficiency	84.05 %	83.97 %	87.57 %	87.48 %
Annual field efficiency	64.20 %	63.00 %	59.21 %	57.16 %
Annual total efficiency	53.96 %	52.89 %	51.85 %	50.00 %
Levelized heat costs	14.03 €/MWh_{th}	14.52 €/MWh_{th}	14.44 €/MWh_{th}	15.09 €/MWh_{th}

Table 2. System performance for different field configurations

3. Liquid Film Receiver

The principle design of the present concept basically consists of a face-down cylindrical receiver, whose inner surface is covered by a directly irradiated molten salt film. Possible applications would be commercial supercritical steam cycles as well as process heat systems. In this context the feasibility of large scale receiver system designs (50 to 400 MW_{th}) is investigated.

3.1 Conceptual design

A schematic layout of the liquid film receiver is shown in Fig. 3. The heat transfer medium enters the receiver at the top with a defined mass flow. Caused by gravity it forms a liquid film with a free surface and flows along the inclined absorber walls. The inner absorber walls of the receiver (e.g. made of SiC) are directly heated by the incoming irradiation which is transmitted through the molten salt film due to its semi-transparent character. As the molten salt is assumed to be transparent in the solar spectrum [16, 17] and absorption bands of the selected salt mixtures exist in the mid-infrared region [18] the liquid film shows a selective behaviour. While flowing along the hot walls the film is gradually heated up from the inlet to the outlet through forced convection and leaves the receiver with a defined adiabatic mixing temperature. Heat transfer by reflection and radiation inside the cavity lead to an additional increase of the absorber wall and film temperature. At the edge of the aperture a trough is installed collecting the downwards flowing liquid film. An insulation layer is built around the outer receiver walls in order to minimize conduction losses to the ambient. For a 250 MW_{th} liquid film receiver optimum aperture diameters are between 7 and 8 m and the receiver height is around 16 m. The side wall inclination lies between 10° and 40° to the vertical and the top wall inclination between 10° and 30° to the horizontal.

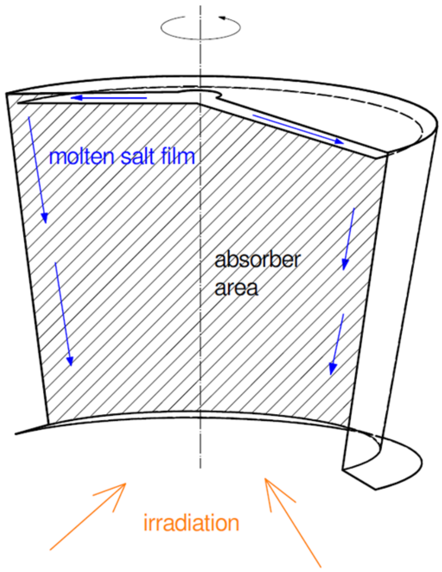

Fig. 3. Principle design of the liquid film receiver

3.2 Research objectives

The thermodynamic issues of the receiver comprise the topic of film stability, receiver system management and enhancement of receiver efficiency. Different system management strategies with rotating or stationary absorber walls with different inclination angles are examined. It is shown that rotating absorber walls with high inclination angles against the vertical exhibit the highest receiver efficiencies. Compared to vertically arranged absorber walls, the inclined walls significantly reduce reflection losses but only slightly increase thermal radiation losses. In contrast to a receiver with stationary absorber walls rotation avoids over-temperatures of the molten salt and increases the film stability. The combination of both allows establishing films which meet the required criteria concerning film breakdown, dry-out and droplet removal at all load conditions.

3.3 Thermal losses

To assess different conceptual receiver designs appropriate CFD models for the calculation of a full size receiver were developed. Free convection losses were assessed with the correlation of Paitoonsurikarn and Lovegrove [19]. The heliostat field layout and irradiation characteristics onto the absorbing walls was carried out with the tools HFLCAL [14] and SPRAY [20]. For a design power of 250 MW_{th} with an inlet temperature of 385° C and an outlet temperature of 620° C the reflection losses are 1.4 % and the thermal radiation losses are 3.9 %. In spite of the open aperture, convection losses are estimated to be about 0.8 % without wind due to the face-down concept, where the hot air is expected to stagnate inside the cavity [21]. Since the vapour pressure of molten salts is sufficient low [22, 23] mass loss due to diffusion is not a critical issue.

4. Falling particle receiver

The falling particle receiver is a promising concept for a highly efficient direct absorption receiver combined with a relative simple design. Preliminary studies have shown that for a design power of 395 MW_{th} and an outlet temperature of 800° C a receiver efficiency of about 90 % can be expected. Applying a favorable operation strategy a receiver efficiency of up to 67 % at 20% part load condition seems possible [24]. The optimum applicable power range for one receiver is expected to be between 50 and 400 MW_{th}.

4.1 Conceptual design

As a heat transfer medium small bauxite particles are used, which exhibit suitable optical characteristics according to previous studies [10]. The absorption coefficient of the particles is about 0.8 – 0.9 and the specific heat capacity is 1000 – 1250 J/kgK for the considered temperature range. However, abrasion of the particles is found to be a critical issue which needs to be assessed thoroughly in subsequent investigations.

Fig. 4 shows a sectional view of a possible receiver design. The particles are transported to a feed hopper at the top of a face-down cylindrical cavity. While the particles fall down through an inlet slit to a collecting ring at the receiver bottom, a free falling curtain parallel to the inner cavity wall is formed. Solar radiation enters the receiver through the open aperture and is directly absorbed by the particle curtain. Similar to the concept of the liquid film receiver convection and radiation losses are reduced due to the face-down design. Furthermore, the particle curtain is protected against wind influence. An efficient recirculation strategy is employed in order to realize optically dense curtains for high absorptivity and hence to increase the receiver efficiency.

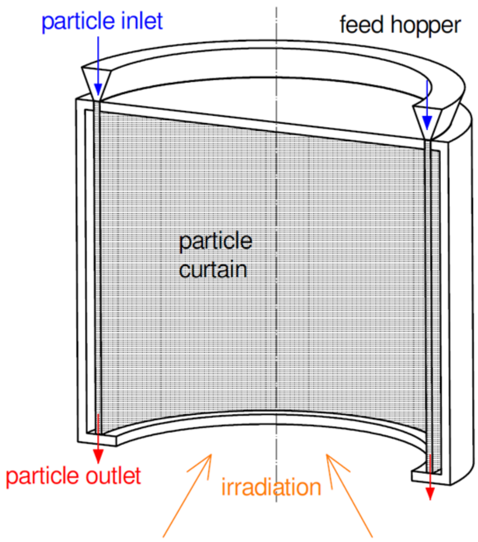

Fig. 4. Principle design of the falling particle receiver

4.2 Research objectives

For design and optimization studies of the receiver, an advanced modular model is currently under development combining CFD simulations with ray tracing methods. Important mechanisms like heat transfer by radiation, convection in a multiphase-flow and particle-fluid interaction will be investigated in detail. For this purpose a novel interface between a CFD and a ray tracer tool is developed. However, it is tried to keep the computational effort low in order to conduct extensive parameter studies to characterize the receiver and assess the sensitivity of the efficiency on different model parameters.

In addition, several experimental setups are under construction demonstrating the feasibility of proposed concept features as well as supporting and validating the simulation data.

4.3 Thermal losses

The thermal receiver efficiency has been evaluated for different load conditions and recirculation patterns using a Matlab based model [24]. For a design power of 395 MW_{th} and a temperature increase from 300° to 800° C, the model predicts about 5 % reflection and 4 % radiation losses when one particle recirculation is utilized. Assuming conduction and convection losses for the face-down concept to be about 1 % a receiver efficiency of around 90 % is found for the given load condition. However, so far no wind influence is considered in the estimation of convection losses.

Preliminary CFD simulations for a face-down cavity with a design power of 3 MW_{th} have been done for different wind speeds (5 – 15 m/s). First calculations without particles lead to convective losses around 2.5 – 6.5 %. These losses are significantly higher than the above mentioned values for no wind (< 1 %). Thus, wind effects are apparently not negligible and need to be considered espescially at large-scale power plants with tower heights up to 300 m. Computational models considering particles, larger receiver sizes and therefore higher receiver power are currently under development.

5. Centrifugal particle receiver

Analogous to the above introduced concepts the centrifugal particle receiver combines high receiver efficiency with a simple and robust design leading to a significant cost reduction potential. It is thought to be well-suited for decentralized small-scale CSP applications in the power range of 0.1 to 1 MW_{th} as well as for systems up to 200 MW_{th}. In combination with a gas turbine, especially for small to medium scale systems, enhanced system efficiencies and advantageous economics seem achievable.

5.1 Concept design

The present concept (see Fig. 5) is based on a fast rotating cylindrical kiln which can be inclined 10 – 90° to the vertical. Due to centrifugal acceleration the heat transfer medium consisting of the same particles as in the second concept are forced against the wall and form a thin but optically dense layer at the whole inner receiver circumference. Gravitation impels the particle layer to slowly move downwards along the wall in axial direction while they are gradually heated up by direct solar radiation entering the open aperture. Since the receiver can be inclined arbitrarily an optimal inclination angle regarding convection losses and heliostat field efficiency can be chosen. In order to achieve a constant outlet temperature at all load conditions the particle retention time and with it the inlet mass flow can be adjusted by regulating the rotation speed. As all losses stay the same under all load conditions optimum part load efficiencies are expected.

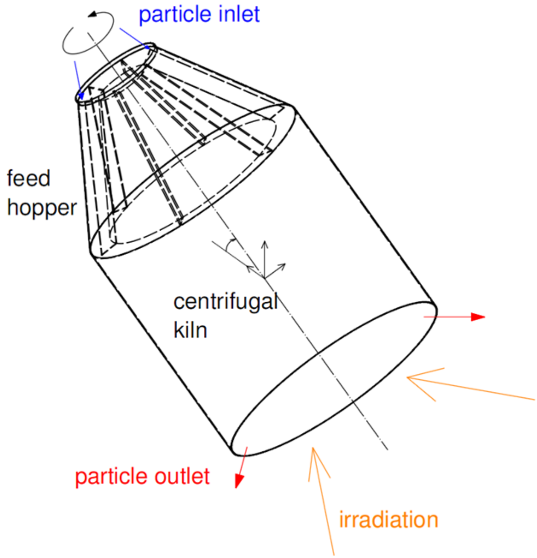

Fig. 5. Principle design of the centrifugal particle receiver

Preliminary dimensioning calculations of the receiver for a 1 MW_{th} power plant, done with HFLCAL, yield an aperture diameter of approx. 1.2 m.

5.2 Research objectives

The particle motion is strongly dependent on the interaction between gravitational and centrifugal force. In order to proof the feasibility of the concept, experiments on the laboratory scale were conducted. Two important features could be demonstrated: First, it is possible to create a dense and thin particle layer covering the whole inner cylinder wall and second, the particle retention time can be indeed controlled by the rotation speed. Note that the experiments were done in a "cold state", where no particle heating was considered. However, future work will include finding a reliable relationship between retention time and rotation speed as well as a detailed study concerning the heating behavior of the particles.

Since the centrifugal superposes the gravitational force additional effects on convectional flow are present.

Therefore, numerical CFD simulations are carried out in order to investigate the influence of rotation on the convectional heat transfer. Comprehensive parameter studies will be done, followed by experimental validation.

5.3 Thermal losses

For a preliminary calculation of the receiver efficiency for a 1 MW_{th} plant, the main thermal losses are estimated. Reflection losses are determined using a ray-tracing tool [20], with the aperture size set to be constant. Different diameter to height ratios are analyzed and as expected, reflection losses decrease with increasing height and diameter. For a proper receiver size with a height to diameter ratio of 1.5 reflection losses of about 3 % are computed, which lies in an acceptable range. Using the Stefan-Boltzmann law the expected radiation losses for an aperture size of 1.13 m² and a temperature range from 600° to 1000° C are calculated to be approx. 9 %. Convection losses are assumed to be between 1 and 5 %, depending on the chosen inclination angle. Wind influences are neglected in this first estimation. Besides, preliminary CFD simulations have shown that for this configuration receiver rotation leads to reduced convection losses. Conduction losses are guessed, as in the above mentioned concepts, to be less than 1 % depending on the insulation thickness around the receiver wall.

6. Conclusion

The design, functional principle, advantages, challenges and first efficiency calculations of three different direct absorption receiver concepts for CSP systems are presented. All proposed concepts feature a simple design, high working temperatures and good storage possibilities leading to a potential reduction of the LEC. One of the main characteristics is the face-down configuration of the receiver, where its open aperture is pointing to the ground. Advantages like reduced convection losses and protection of the heat transfer medium from wind influences are the consequence. Field layout calculations have shown relatively small differences regarding annual performance and levelized heat cost between a face-down receiver and a receiver with optimized inclination angle. However, only a simplified receiver efficiency model is considered in the HFLCAL calculations, neglecting convection losses. In order to make conclusions about the final optimal configuration convection losses depending on the inclination angle need to be taken into account. An overview of the main receiver facts is listed in Table 3. First estimations revealed comparatively high receiver efficiencies for the design power ranges. However, appropriate models and experiments will be set up in order to verify preliminary findings and to evaluate critical issues.

	Liquid film receiver	Falling particle receiver	Centrifugal particle receiver
Power range	50 – 400 MW_{th}	50 – 400 MW_{th}	0.1 – 200 MW_{th}
Heat transfer medium	Molten salt	Ceramic particles	Ceramic particles
Tower height*	100 – 300 m	100 – 300 m	25 - 200 m
Aperture diameter	7 – 18 m	8 – 20 m	0.3 - 15 m
Inclination angle	90°	45° – 90°	10° – 90°
Max. outlet Temperature	620° C**	1000° C	1000° C
Estimated design point efficiency	94.5 % (385° C in, 620° C out)	90 % (300° C in, 800° C out)	83 % (600° C in, 1000° C out)

* With Multi-Tower systems and a higher number of tower modules lower towers can be achieved.
** High temperature salts support temperatures up to 1200° C [23].

Table 3. Overview of the different DAR concepts

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