First tests of a centrifugal particle receiver with a 1m^2 aperture

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First Tests of a Centrifugal Particle Receiver with a 1m^2 Aperture

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Abstract. Particle receivers achieve significantly higher temperatures than state of the art molten salt solar towers. The centrifugal particle receiver is a direct absorption receiver with a simple control of the residence time of the particles in the receiver. The paper describes the cold testing including mechanics of the particle film and first hot testing using a 100 kW_{el} infrared heater.

INTRODUCTION

The temperature limit of direct absorption receivers is defined by the temperature limit of the heat transfer medium and the insulation. The centrifugal particle receiver already demonstrated outlet temperatures of 900°C at lab-scale [1,2]. A prototype with an aperture area of 1 m^2 (1.13 m diameter) and an internal absorber chamber diameter of 1.6 m and height of 2.3 m for commercial use of up to 2.5 MW_{th} has been built [3]. With a predicted efficiency of >90% at 900°C particle outlet temperature, 200°C particle inlet temperature and low production costs, a cost-competitive system is expected [4]. Next to electricity production the high temperature and the integrated storage opens new high temperature process heat applications, for example preheating to save electricity in induction furnaces [4].

PARTICLE FILM MECHANICS

The particle film is the key to the performance of the receiver. Thermodynamically an opaque yet thin particle film with a constant particle movement in each turn of the receiver is desired. Particle movement in the rotating receiver is governed by a superposition of gravitational force and centrifugal force. The alignment of these forces changes during one turn if the rotational axis is not vertical. We use an inclination of 45° of the rotational axis against the vertical which results from an optimal alignment of the aperture from the heliostat field optimization. Gravitational force and centrifugal force act together in the lower half of the receiver and stop the particle movement by pushing it against the inner wall (see figure 1, long blue arrow). They counteract each other in the upper part where the particles move as they are not pushed strong enough against the wall to make them stay (see figure 1, short blue arrow). As the moving particles in the upper part are always at the same position from a non-rotating viewpoint they form a standing wave.

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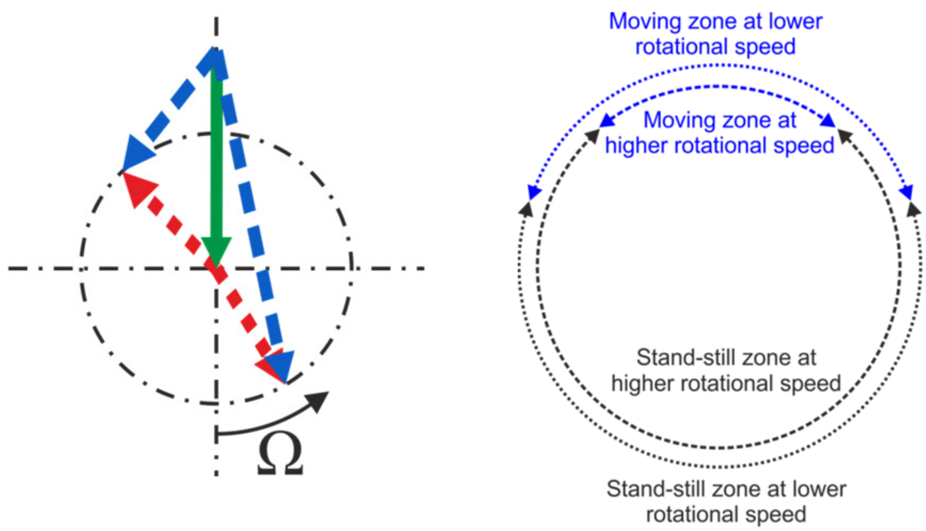


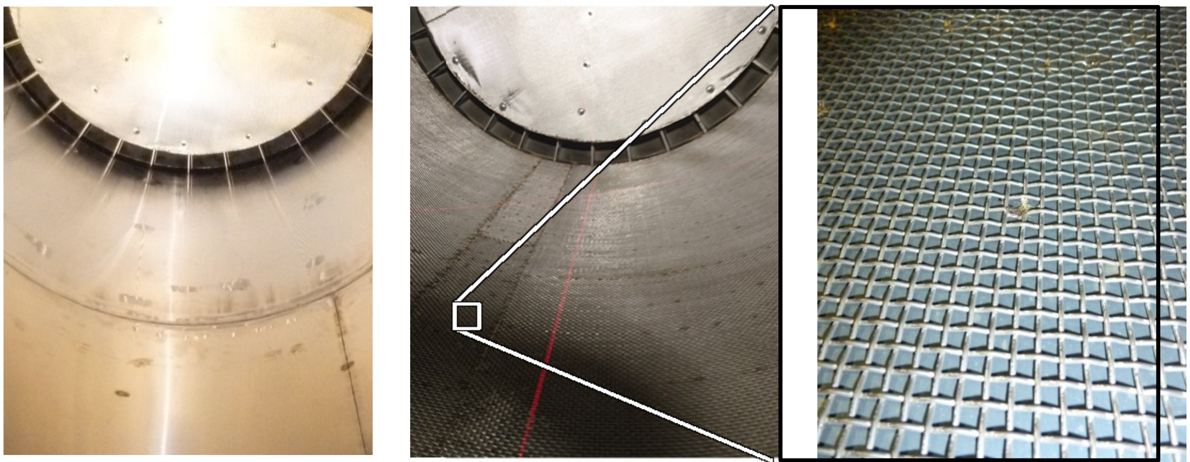
FIGURE 1. Left: Superposition of gravitational force (green, one dash) and centrifugal force (red, small dashes) to the resulting force (blue, longer dashes) on the particles for two different particle positions on the circumference Right: Changing moving zone width with changing rotational speed

The gravitational force has also an axial component, which forces the particles towards the aperture in a stepwise manner during each turn. By varying the rotational speed the duration the particles move in the upper part - and thus the width of the movement zone or standing wave - can be changed as shown in figure 1 on the right. This controls the step-size towards the exit at the aperture during each turn, effectively controlling the residence time of the particles in the receiver. Together with a particle mass flow control into the receiver the desired outlet temperature can be achieved under any load conditions. As the particle film is then also always opaque the relative reflection loss (ratio of reflection loss to the solar radiation entering the receiver) stays the same for all load conditions. Thermal emission losses, conductive losses through the insulation and convection losses at constant wind conditions are constant once the stationary design inlet and outlet temperature are reached and independent of the receiver load.

The absorber chamber is built from an outer load bearing metal shell, 100 mm of inner insulation and an inliner of 2 mm Inconel 617 facing the particle film. First cold tests with a smooth metal inliner (see Figure 2 a) did not produce a desirable particle film. At rotational speeds lower than 53 rpm no closed particle film developed as the particles slid down the inliner. At higher rotational speeds no continuous particle movement was achieved as particles did not slide but accumulated in the receiver for some minutes and then left the receiver within few turns in large avalanches.

With the smooth wall the friction coefficient between the particles and the wall was lower than between two particle layers resulting in particles sliding on the complete circumference at lower rotational speeds. At higher rotational speeds the particles begin to stick, but then many layers of particles accumulate on top because of the higher friction coefficient between particle layers until all particles move in large avalanches.

The solution for a constant particle movement in each turn was a wire mesh point-welded on the smooth inliner as shown in Figure 2 (b and c) providing a rough surface for the film. The used wire mesh has a wire diameter of 1.2 mm and a mesh width of 4 mm. The material is 1.4841, a stainless steel with high temperature corrosion resistance. With the wire mesh an optically dense particle film already formed at much lower rotational speeds of about 43.5 rpm, where the particles move during each turn. Particles move into the wire mesh and are blocked in the axial direction by the tangential wires of the mesh because the wire diameter is larger than the average particle diameter of 1 mm. By this a rough surface on the inliner is formed with the same friction coefficient between the moving particles and the wall as between two particle layers.



a) b) c)

FIGURE 2. Receiver inliner a) without wire mesh, b) with wire mesh and c) close-up of the wire-mesh

The thickness of the moving particle film $\boldsymbol{s_{mpf}}$ depends on the particle mass flow $\boldsymbol{\dot{m}_p}$ through the receiver and the rotational speed $\boldsymbol{\omega}$. The mass flow is adapted to achieve the desired receiver outlet temperature and is governed by the incoming solar radiation power and the receiver efficiency. With the given particle bulk density $\boldsymbol{\rho_p}$ the particle volume flow $\boldsymbol{\dot{V}_p}$ is directly proportional to the mass flow. In stationary conditions the cross section of flowing particles $\boldsymbol{A_{Pf}}$ at the radius of the wire-mesh $\boldsymbol{r_{wm}}$ grows with more particle volume flow $\boldsymbol{\dot{V}_p}$ and lower average axial particle speed $\boldsymbol{v_{p,ax}}$:

$$\boldsymbol{A_{Pf} = \pi \cdot (r_{wm}{}^2 - (r_{wm} - s_{mpf})^2) = \dot{V}_P / v_{p,ax} = \frac{\dot{m}_p}{\rho_p \cdot v_{p,ax}}}$$

The particle film thickness can then be calculated from $\boldsymbol{A_{Pf}}$. For a given mass flow the film thickness grows with higher rotational speeds because the particles move slower. The thickness of the film can therefore be optimized for minimum receiver losses. In a too thin film significant absorption of incoming solar and thermal radiation will happen in the stationary base layer. This base layer will heat up to higher temperatures than the moving particle film above and radiate to the ambient with higher losses than if all the solar radiation would be absorbed in the moving layer. A minimum thickness of only a few particles is needed for full absorption in the moving particles. But a larger film thickness results in a larger temperature difference between the front side and the back side of the moving particle film due to higher absorption of radiation at the inside. The particles on the inside move slower due to the stationary rough wall, reducing the temperature difference to the front side. Furthermore mixing of particles with overflowing particles due to relative tangential movement resulting from the tangential component of the gravitational force will happen. A thicker particle film is also expected to be less sensitive to geometric tolerances of the inliner. The optimal film thickness is the one resulting in the highest outlet temperature which equals the lowest surface temperatures for a given particle mass flow and receiver power.

The weight of particles can be measured in the receiver with load cells in the bearing system. This allows calculating the actual particle film thickness from the particle weight and the receiver surface. A typical amount of particles in the receiver is about 100 kg resulting in a particle film thickness of about 4 mm or approximately 4 particle layers. It is planned to change the particle film thickness in the tests and determine the thermodynamically optimal conditions experimentally.

An oversized electric motor of 7 kW is used to turn the receiver. The parasitic electricity consumption at full receiver power (2.5 MW_{th}) assuming a power block efficiency of 40% is thus only 0.7%. At 900°C particle outlet temperature, 200°C particle inlet temperature the particle mass flow at 2.5 MW_{th} is 3 kg/s. The theoretical power needed to accelerate these particles to 43.5 rpm at 0.8 m radius is only 19.9 W. Therefore most of the electric energy is used to overcome friction in the drive system and seals.

TEST RIG

For a first off-sun test campaign of the receiver a test rig with a 100 kW electric heating system (see Figure 3) was built in a hall in Stuttgart/Germany in 2015/2016 [3]. Particles at ambient temperature are supplied into the rotating receiver from a silo which is located above the receiver through a transfer pipe (see Figure 4, only partly shown in Figure 3) consisting of 2 parts. Through this transfer pipe the particles move from the stationary part upstream of the receiver into the rotating receiver. Mass flow into the receiver is controlled through a self-build rotating gate valve between the two parts of the transfer pipe (see Figure 4). The rotating gate has the form of a half cylinder which rotates around an axis in the upper part of the transfer pipe. In the closed state the outlet of the upper transfer pipe is completely located under the upper limits of the half cylinder which blocks particle movement even if the test rig is vibrating significantly. For better dosing precision at low particle mass flows a cut in V-form is used in the half cylinder allowing only few particles next to each other pass through the valve when it begins to open. A distance of more than three maximum particle diameters between the upper transfer pipe and all parts of the rotating gate allow a smooth rotation without jamming due to particle bridging.

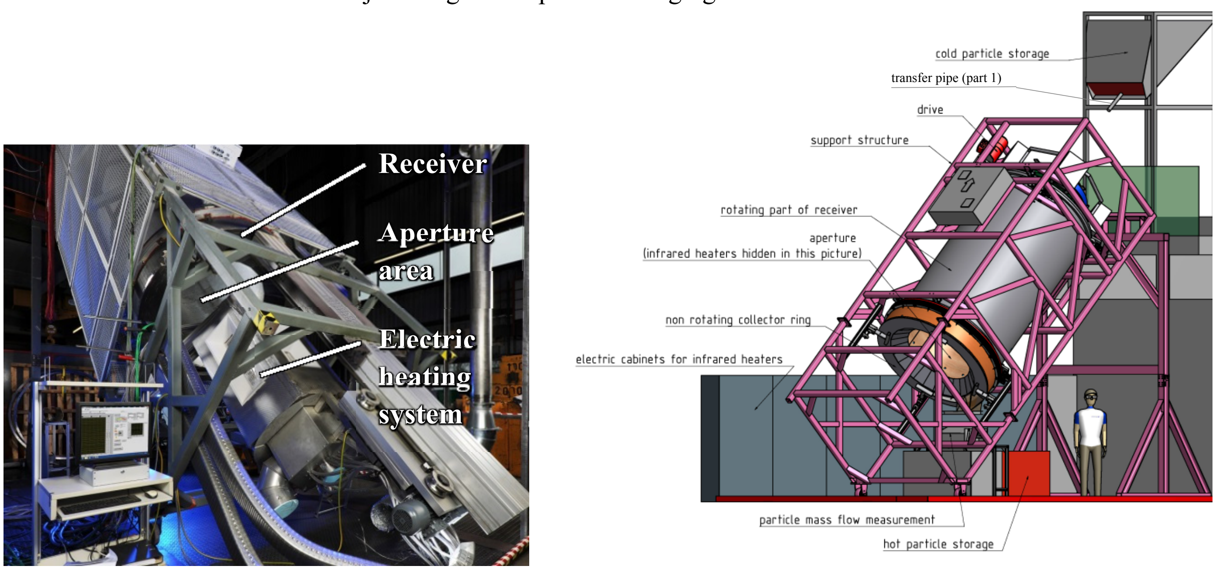


FIGURE 3. Left: Receiver with 100 kW$_{el}$ infrared heating system in maintenance position outside of the receiver. Right: Test rig overview (without electric heating system)

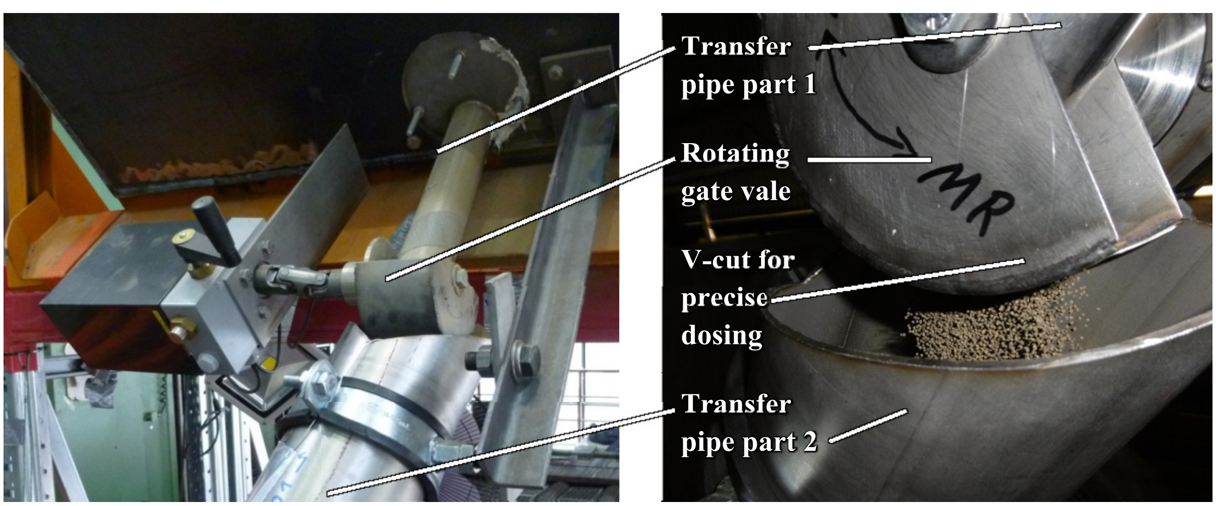


FIGURE 4. Left: Overview of the transfer pipe and rotating gate valve. Right: Close up

In the rotating receiver inlet the particles move between two cones with an axial distance. Radial ribs between these cones accelerate the particles to the rotating receiver. Gravitational and centrifugal forces move the particle through this acceleration structure into the absorber chamber where they form a film on the complete circumference as described in the cold testing chapter of this paper. More details of the receiver interior are given in [3].

Temperatures of the rotating absorber chamber were measured with 39 thermocouples installed between the 2 mm Inconel 617 inliner and the microporous insulation (see Figure 5). Due to good thermal contact and low heat flux through the insulation these thermocouples measure local particle temperatures. The TC signals were processed in rotating electric cabinets and send through Wifi to the main data acquisition system

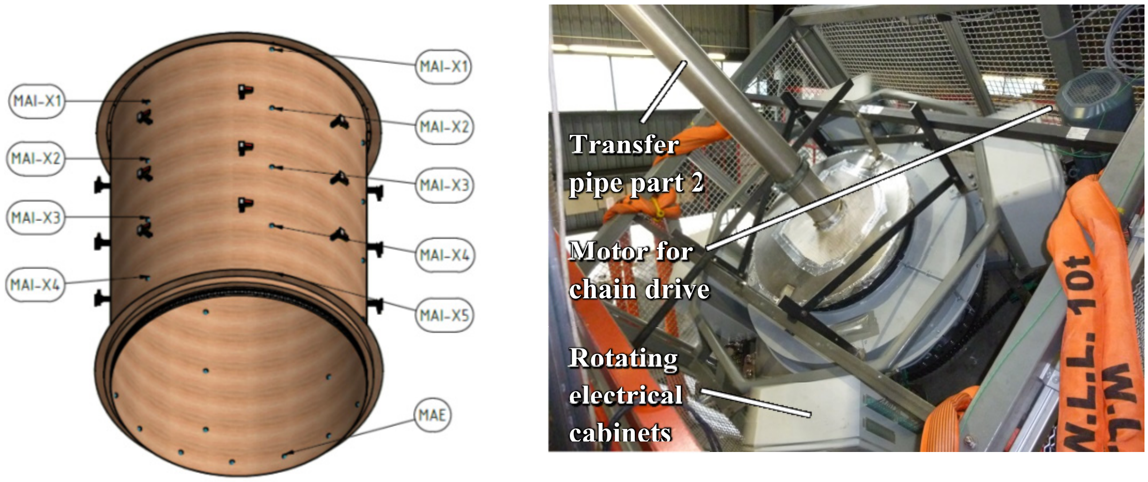


FIGURE 5. Left: Postions of TCs on the absorber chamber inliner . Right: 4 rotating electric cabinets with the TC electronics and a Wifi system

After passing through the absorber chamber the particles leave the receiver as they fall off the rotating absorber chamber at the lower end. This lower end is enclosed by a torus-shaped stationary collector ring which guides the particles to the outlet under the aperture. There particles are collected in a buffer storage, cooled if necessary and transported back into the silo above the receiver.

The electric heating system consists out of ten 10 kW Superthal IR radiators manufactured by Kanthal. The resistance heating elements manufactured from $MoSi_2$ allow temperatures >1750°C and power densities for the complete element of 300 kW/m^2. A quartz window before the heating elements protects them from ambient influences like dust. Depending on the temperature of the irradiated objects the electric power input into the heating elements has to be reduced due to the additional heat input from the thermal radiation coming from the irradiated objects. The used power electronics allow permanent element temperature surveillance and input power control based on the temperature dependant resistance of the $MoSi_2$ material to avoid overheating.

The ten radiator elements were combined to one electric heating system as seen in Figure 6 on a common sheet metal frame. Ceramic cones around the radiators and a thermal insulation based on microporous material covered with a high temperature stainless steel foil fill the space between the radiators. Forced air cooling through the sheet metal frame inside the system keep the electric connections of the radiator elements below 80°C. A linear drive system was used to move the electric heating system into the receiver for hot testing and out of the receiver for cold testing and maintenance.

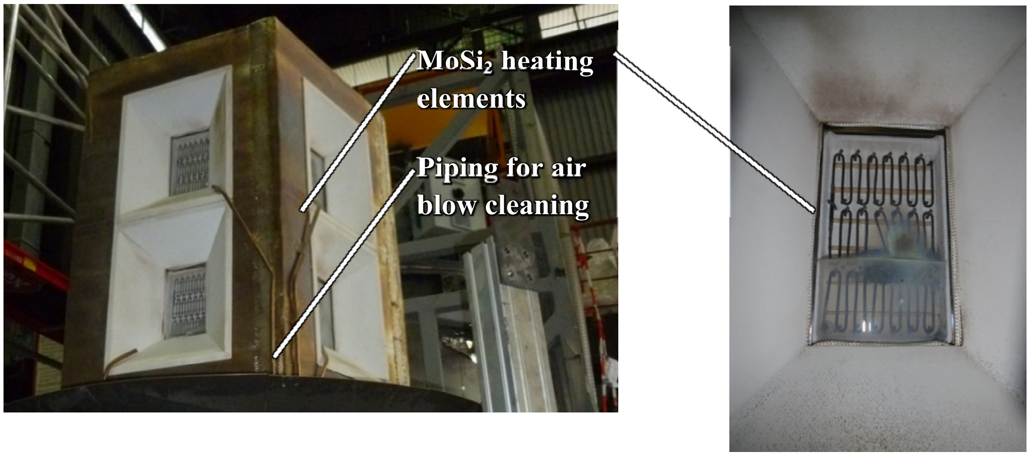


FIGURE 6. Left: 100 kW electric heating system based on $MoSi_2$ heating elements. Right: Broken heating elements

Due to particles in front of the quartz windows of the infrared heaters the MoSi2-wires of several heater elements were blown (see Figure 5 right). To prevent the build-up of stray particles in front of the radiator elements a cleaning system based on air blowing was installed (see Figure 5 left). Pipes from a high temperature stainless steel supplied air to nozzles with 2 mm diameter angling at the corners where particles build up. 1 s pulses of 7 bar air to the noozles avoided particle build-up. The air flow removed less than 2 kW_{th} from the receiver when it leaves it hot through openings like the gaps between the rotating and stationary parts.

HOT TESTING WITH A 100 KW_{EL} INFRARED HEATER

The receiver was started with 43.5 rpm and a particle mass flow of 0.4 kg/s. At this condition a continuously moving particle film developed. Then to speed up the heating with the limited power the rotational speed was set to a value of 45.2 rpm where the particles don't move on the complete circumference ("frozen particle film"), mass flow was stopped and the heating system was turned on. Up to 700°C were reached on the receiver inliner on test day August 24, 2016 (see Figure 7). At the end of the test the rotational speed was reduced, so hot particles left the receivers. Up to 400°C at the receiver outlet were measured an August 31, 2016 (see Figure 8) with a temperature of the receiver inliner of 500°C.

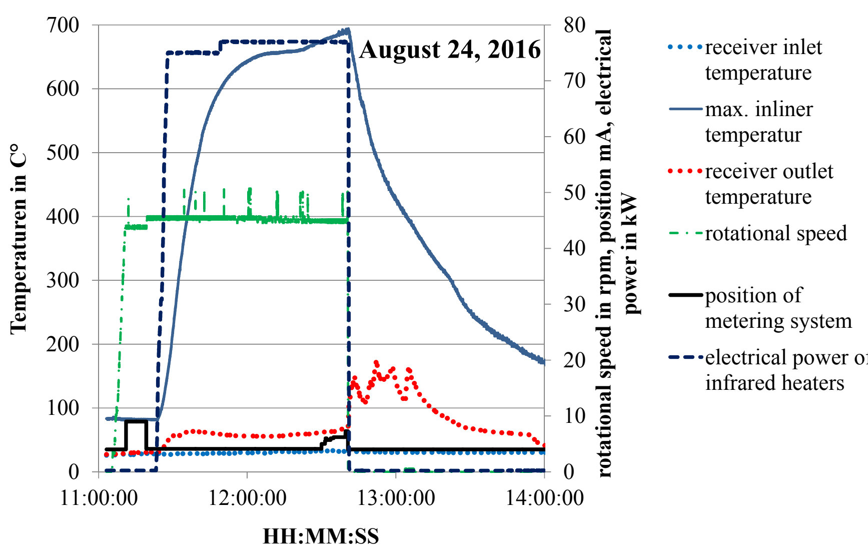


FIGURE 7. test day 24th of August 2016, receiver inlet temperature of 700°C achieved

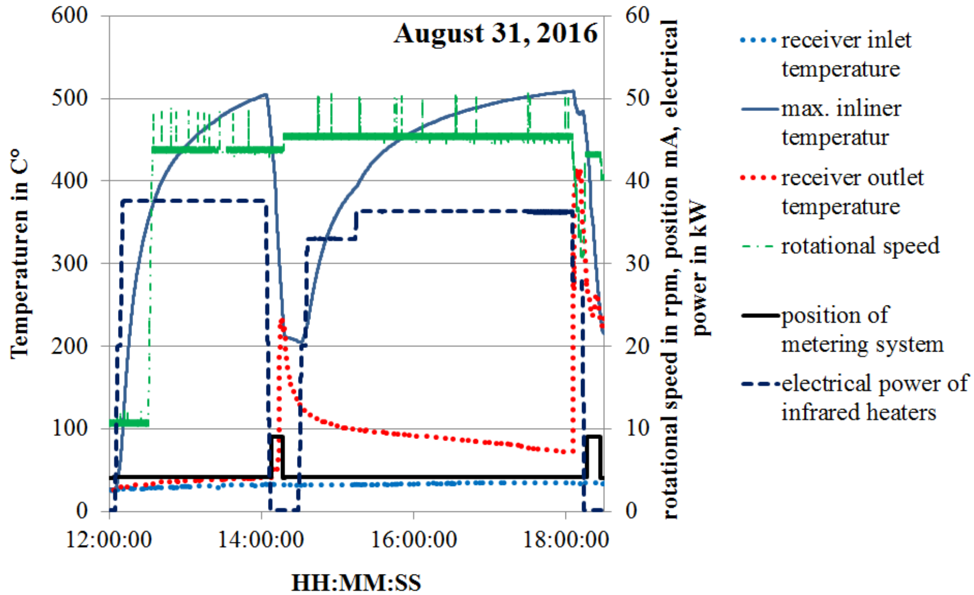


FIGURE 8. test day 31st of August 2016, receiver outlet temperature of 400°C achieved

This failure of the electric heating system due to particle build-up and the necessary time for the reparation and installation of the cleaning system before the shipping of the receiver to the solar test facility in Jülich prevented higher particle temperatures with the electric heating system. In total 55 hours of rotational tests have been carried out of which 26 hours were hot testing with an operating heating system.

OUTLOOK

Receiver on-sun tests up to 500 kW_{th} with a targeted outlet temperature of 900°C are planned on the Solar Tower Jülich for autumn 2017.

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