Operational experience of a centrifugal particle receiver prototype

Cite as: AIP Conference Proceedings **2126**, 030018 (2019); https://doi.org/10.1063/1.5117530
Published Online: 26 July 2019

Miriam Ebert, Lars Amsbeck, Jens Rheinländer, Bärbel Schlögl-Knothe, Stefan Schmitz, Marcel Sibum, Ralf Uhlig, and Reiner Buck

Operational Experience of a Centrifugal Particle Receiver Prototype

Miriam Ebert[1, a)], Lars Amsbeck[1, b)], Jens Rheinländer[1, c)], Bärbel Schlögl-Knothe[2, d)], Stefan Schmitz[2, e)], Marcel Sibum[2, f)], Ralf Uhlig[1, g)], Reiner Buck[1, h)]

[1]*German Aerospace Center, Institute of Solar Research, 70569 Stuttgart, Germany*
[2]*German Aerospace Center, Institute of Solar Research, 52428 Juelich, Germany*

a)Corresponding author: Miriam.Ebert@dlr.de
b)Lars.Amsbeck@dlr.de
c)Jens.Rheinlaender@dlr.de
d)Baerbel.Schloegl@dlr.de
e)Stefan.Schmitz@dlr.de
f)Marcel.Sibum@dlr.de
g)Ralf.Uhlig@dlr.de
h)Reiner.Buck@dlr.de

Abstract. The centrifugal particle receiver "CentRec" is a solar tower receiver development by DLR based on a direct absorption receiver concept especially suitable for high temperature process heat and electricity generation applications. Ceramic particles are used as heat transfer and storage medium for temperatures up to 1000°C. A centrifugal particle receiver system including a CentRec receiver prototype has been tested up to 965°C average receiver outlet temperature in the research platform of DLR's test facility Juelich Solar Tower, Germany. This paper describes the first test results with a focus on first operational experiences.

INTRODUCTION

Further cost reductions compared to current solar tower technologies like molten salt can be achieved by using ceramic particles as heat transfer and storage medium. The principle of direct absorption receivers using ceramic particles as heat transfer medium has been investigated since the 1980`s in the USA by Sandia and has been identified as one option to meet the SunShot goal of 6 $c/kWh [1]. Cost reductions are possible thanks to the application of more efficient turbines, higher storage densities and lower component costs. The technology allows also the supply of high temperature heat for industrial applications or fuel production [2, 3] and combined heat and power.

The feasibility of particle receiver and system components at high temperature still has to be shown at demonstration plant size. Several steps towards this demonstration have been already successfully conducted for the CentRec technology:

- Proof-of-Concept with a receiver prototype of 7.5 kW_{th} power in a solar furnace [4].
- Upscaling of the receiver to 2.5 MW_{th} power in a commercial setup for a future pilot plant [5].
- Lab tests of a 2.5 MW_{th} receiver prototype with infrared heaters [5, 6].
- On-sun test of the prototype up to 965°C receiver outlet temperature in a test setup in the research platform of the Juelich Solar Tower (STJ) [7] in Juelich, Germany [8].

In the last step, not only the receiver but also other challenges identified in the "Gen3 Demonstration Roadmap" [1] like particle loss and transport system has been addressed and tested and observations are presented in this paper.

SolarPACES 2018
AIP Conf. Proc. 2126, 030018-1–030018-8; https://doi.org/10.1063/1.5117530
Published by AIP Publishing. 978-0-7354-1866-0/$30.00

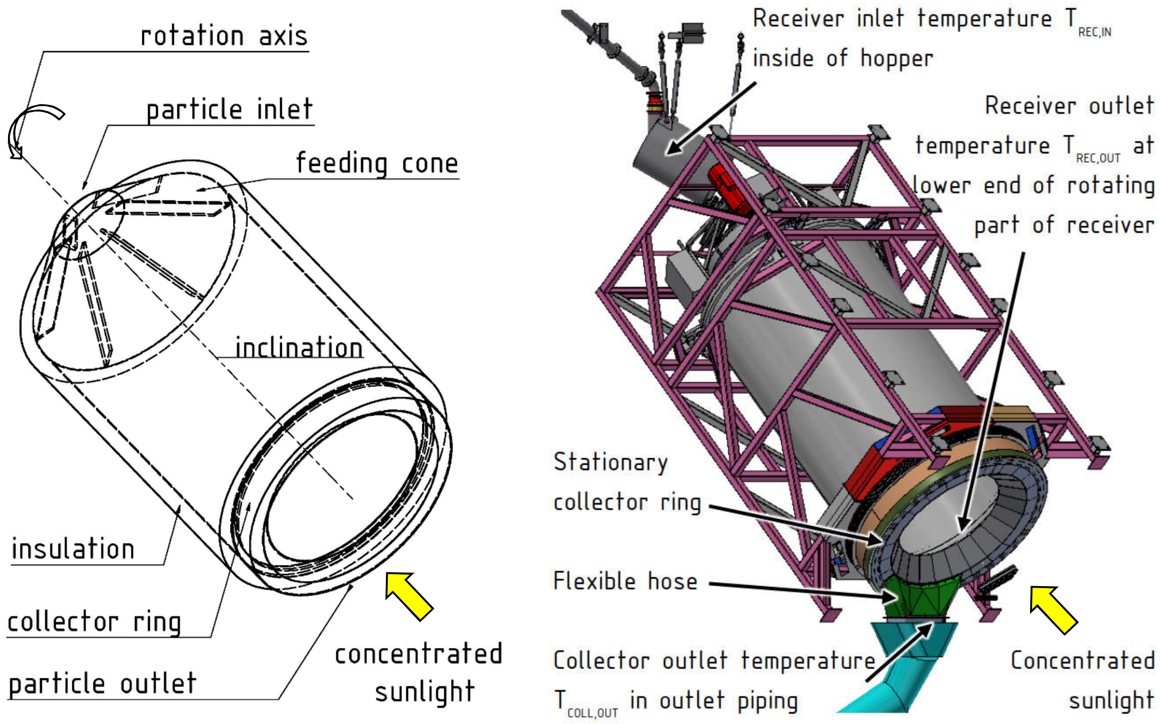
TEST SETUP

The test setup consists of a CentRec receiver prototype with 2.5 MW_{th} power (in commercial configuration) integrated into the research platform of the STJ and a closed loop particle transport system including storage and particle cooling.

The CentRec concept is based on an inclined, rotating drum where cold particles are fed into the system on the top using a feeding cone and leave the receiver on the bottom into a collector ring with particle temperatures up to 1000°C. The scheme of the concept is shown in FIGURE 1 (a). Inside the receiver the particles are accelerated by centrifugal and gravitational forces. The particles are directly irradiated and thus heated from the incoming concentrated sunlight through the aperture on the bottom. The receiver is equipped with more than 100 thermocouples to monitor, control and evaluate the temperatures. The positions of the most important thermocouples are shown in FIGURE 1 (b):

- The receiver inlet temperature $T_{REC,IN}$ is measured inside the particle hopper at the inlet of the receiver.
- The receiver outlet temperature $T_{REC,OUT}$ is determined by thermocouples positioned on the rear side of a metallic surface on which the particles move down just before leaving the rotating receiver. Thus, these temperatures correspond very closely to the particle temperatures at this position.
- The collector outlet temperature $T_{COLL,OUT}$ is measured downstream the outlet of the stationary collector ring. Therefore part of the particle mass flow is retained inside a measuring cup to be able to measure the particle temperature inside a small particle bed.

A more detailed description of the receiver (design and manufacturing including measurement system and former pre-tests) and the particle loop test setup are given in [5], [6] and [8].



(a)[5] (b)

FIGURE 1. Scheme of CentRec receiver (a), position of relevant thermocouples (b)

TESTS

After commissioning in September 2017 first tests aiming at high receiver outlet temperature have been carried out. During winter season on-sun tests are not possible due to very low sun elevation angles and cloudy sky conditions in Juelich. Therefore, cold particle tests have been conducted and evaluated using video records to optimize the operation parameters for different part-load operation ranges. Additionally, an overhaul of the system and maintenance work have been carried out. In spring, on-sun tests have been restarted to further increase the outlet temperature and conduct steady-state operation at different temperatures. As the heliostat field at the STJ is not optimized for small, high flux density receivers on the research platform at 26 m height, tests could only be conducted up to 400 kW/m² flux density in the aperture. Thus, only part load tests at low particle mass flow have been realized and very high spillage had to be accepted during operation (see FIGURE 2). The test period finished on 25th of June 2018 with the start of the dismantling of the system to make the research platform available for another project. 0 shows the integrated receiver during on-sun operation.

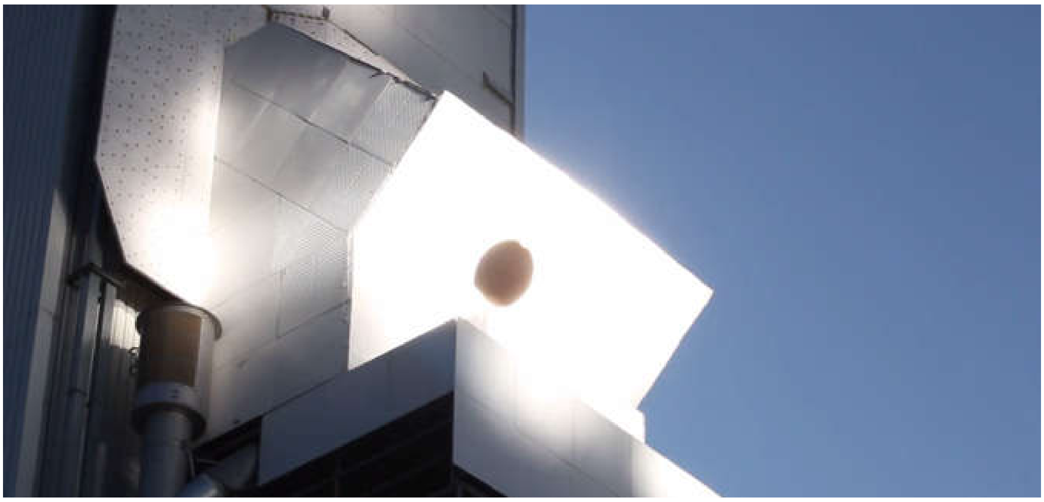


FIGURE 2. View of receiver during on-sun operation

RESULTS

Between September 2017 and end of June 2018 nearly 70 h of receiver on-sun operation have been conducted. The whole particle system including receiver, transport system and valves have been operated for more than 125 hours. TABLE 1 gives an overview of all conducted on-sun tests of the CentRec system.

The highest receiver outlet temperature $T_{REC,OUT}$ of 990°C has been reached on test day 22 on 4th of May 2018. FIGURE 3 gives an overview of the test showing a sunny day with nearly 900 W/m² DNI and up to approximately 600 heliostats focused on the receiver. The rotational speed of the receiver and the particle mass flow have been maintained constant during the test with approximately 45 rpm and a mass flow range of 0.07 – 0.18 kg/s, respectively. Besides the receiver inlet temperature $T_{REC,IN}$ the values of three sensors of the receiver outlet temperature $T_{REC,OUT}$ are plotted. Additionally one of the three thermocouples at the collector outlet $T_{COLL,OUT}$ is given (dashed line). The test has been interrupted two times by an automatic emergency shut down caused once by a broken thermocouple and thus a misinterpretation of temperature by the Programmable Logic Controller (PLC) and once by a failure in the frequency converter of the drive of the receiver. After the emergency shut down a fast reheating of the system can be observed. In the second test more than 20 minutes of operation at an average receiver outlet temperature of more than 900°C, with a maximum average outlet temperature of 965°C, have been achieved.

TABLE 1. Overview of on-sun tests

N° of test	Date DD.MM.YYYY	Operating hours on-sun in hh:mm	Max. collector outlet temperature $T_{COLL,OUT}$ in °C	Max. receiver outlet temperature $T_{REC,OUT}$ in °C
1	24.09.2017	03:01	100	120
2	25.09.2017	02:52	370	420
3	27.09.2017	03:20	500	550
4	29.09.2017	01:07	500	595
5	06.10.2017	00:32	50	50
6	12.10.2017	05:10	350	420
7	14.10.2017	04:00	650	700
8	17.10.2017	01:42	330	355
9	18.10.2017	03:16	775	910*
10	19.10.2017	02:17	725	940*
11	27.10.2017	00:51	250	345
12	13.11.2017	00:35	140	225
13	17.11.2017	02:00	400	575
14	22.11.2017	02:52	500	690
15	06.04.2018	02:18	325	630
16	18.04.2018	02:15	210	480
17	19.04.2018	02:35	165	240
18	20.04.2018	03:14	375	550
19	21.04.2018	04:17	430	675
20	02.05.2018	03:08	290	380
21	03.05.2018	05:13	410	555
22	04.05.2018	03:47	840	990
23	15.06.2018	02:30	340	660
24	20.06.2018	05:26	480	700
Sum		68:18		

*very short duration

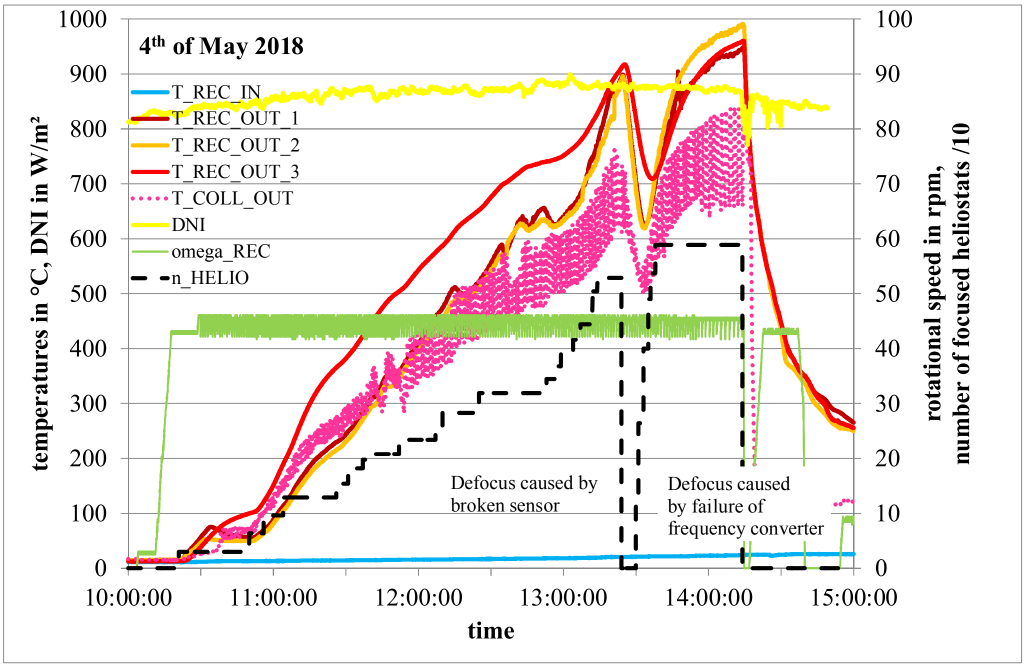


FIGURE 3. Overview of test day 4th of May 2018 with receiver outlet temperature of more than 900°C

Two other observations that can be made in FIGURE 3 are the high difference between receiver and collector outlet temperature $T_{REC,OUT}$ and $T_{COLL,OUT}$ and the variation of the rotational speed $\omega_{RECEIVER}$ and of the collector outlet temperature $T_{COLL,OUT}$.

This is caused by a special operation mode used for small mass flows (<20 % part load):

Mass flow and particle film reacts very sensitive on changes in circumferential speed. One reason for changes in the circumferential speed are manufacturing tolerances of the metallic surface on which the particle layer moves down. Especially for low mass flow rates inhomogeneities of the particle film could be observed. A homogenous particle film can be achieved by a periodic acceleration and deceleration of the particles by changing the rotational speed. Lower rotational speed makes the particle move faster, higher rotational speed stops the particle movement (the film is "freezing"). To additionally control the mass flow and the receiver outlet temperature a dwell time at the higher rotational speed can be changed. Further details are given in [8]. Applying this operation mode particles leave the receiver only each time the rotational speed is reduced. In the present test day the mass flow corresponds to 5% part load. As the measurement cup has been designed for higher mass flows, this mass flow is too low to retain a sufficient amount of particles in the measurement cup to cover the thermocouples. Thus, thermocouples in the cup only measure the particle temperature at the collector outlet for a very short instance of time before being uncovered again and measuring the colder temperature of the piping and the air. The correlation between rotational speed and temperature can be observed in detail in FIGURE 4. During the retention time in the particle bulk inside of the measurement cup the temperature measurement is still increasing fast. The temperature measurement thus probably underestimates the real temperature. Therefore this measurement is not reliable at low mass flows with the current measurement cup design. This observation explains the high temperature difference between receiver and collector outlet temperature.

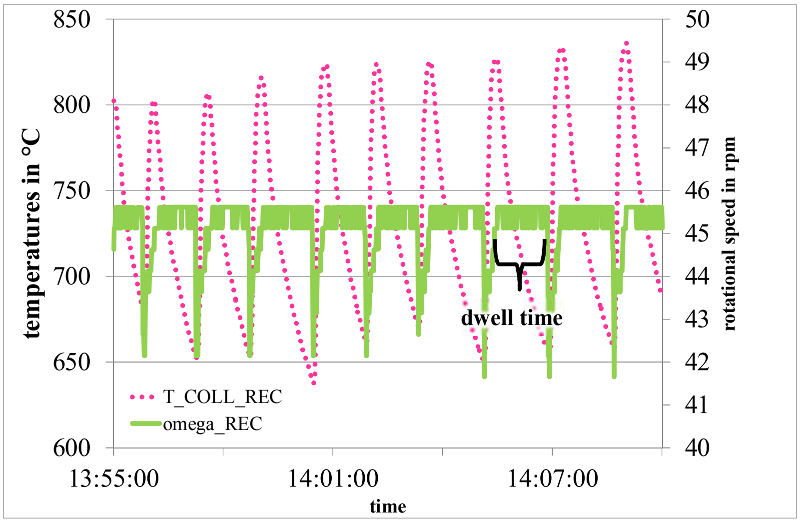


FIGURE 4. Detail of test day 4th of May 2018 with rotational speed and collector outlet temperature

System

Several observations during and after the tests have been made that indicated reliability of components or possible further improvements. The following components of the receiver and the system have been checked more in detail. The evaluation has been done by evaluation of data and visible inspection after the tests without destructive methods as the receiver should be reused again.

- Inner surface of receiver:
  A welded wire mesh is used to increase wall friction for better particle film behavior [6]. This wire mesh was retrofitted after manufacturing of the receiver and not foreseen at the beginning of the design. The wire mesh material has a slightly higher thermal expansion as the metal surface beneath and has been welded on the metal surface. As consequence, no free thermal expansion along the receiver wall can take place. Furthermore, the wire-mesh heats up faster during start-up than the underlying metal

surface. As a result the mesh partly lifted up from the wall [FIGURE 5] and thus did not provide a satisfying surface characteristic for a homogenous particle film anymore. It needed to be substituted by another design where smaller elements of wired mesh were fixed using welded, bent bolts on which the mesh is only hooked in and therefore allows for thermal expansion along the receiver wall [FIGURE 6].

- Particle loss through aperture:
  During operation it could be observed that a certain amount of particles leaves the receiver not through the collector ring but through the aperture [FIGURE 8]. A detailed quantitative evaluation of the amount is difficult to obtain. On one test day a very rough estimation of the particle amount on the ground after test has been done that led to particle loss of approximately 5 % of the particle mass flow for that test day. The main cause for the particle loss could be identified: the insulation of the rotating part of the receiver has a thermal expansion joint. It is positioned at the lower end of the receiver, approximately 100 mm before the outlet to the collector ring. This expansion joint must not be blocked with other components to allow free thermal expansion of the metal surface covering the insulation. Thus, the retrofitted metallic wire mesh on the inner side of the receiver does not cover the last 100 mm of the lower part of the surface of the receiver. Due to the smooth surface in this area, friction between particles and wall is to low and particles bounce out of the receiver. It has been observed that mainly particles coming from this uncovered area leave the receiver. Considering the required roughness of the surface in a future redesign, the particle loss can be reduced significantly.
- Particle loss through junction between rotational and stationary collector ring:
  The sealing of particles and hot air between the rotating receiver and the stationary collector ring is done by a number of radially interlocked metal sheets. Manufacturing tolerances for insulated sheet metal components have been underestimated and adaptions were required. Especially during shut down procedure particles, and thus dust, partly leave the receiver through the sealing. The design of the sealing will be improved in the next generation of this receiver technology.
- Belt bucket elevator:
  The belt bucket elevator used as transport system showed no wear after the tests [FIGURE 7].
- Bearing of the receiver:
  From the former project the receiver sums additional 55 operational hours, so in total 180 operational hours. Assuming an average rotational speed of 45 rpm of the receiver the load on the bearing results in approximately 486,000 cycles. The bearing showed no visible wear although present dust caused by the particle loss mentioned before mixed with the lubricant [FIGURE 9]. This should be avoided by improving the sealing or optionally encasing the bearing system.
- Inner insulation of the receiver:
  The bearing temperature stayed below the required value of less than 120°C (limit for lubricant and sealing of bearing) and the outer metallic vessel of the receiver stayed below 100°C (value that results of the range of the validity of the stress analysis for the material) which indicates an intact insulation. Further investigations on insulation exposed to vibration and humidity from ambient should be done.
- Valves:
  The squeezing valves used as mass flow control valve for the receiver and the clamshell gate valve used as mass flow control valve for the transport system showed no wear after the tests. But the temperature limit of only 80°C of the rubber sleeve of the squeezing valve doesn't allow applications with higher particle inlet temperatures.
- Particles:
  Impurities have been observed in the system. These impurities led to problems in the inlet piping were the filter got clogged very fast and inhibited the particle flow to the receiver and in the measuring cup where the inhibited mass flow influenced the temperature measurement. The impurities partly entered into the system during installation (parts of insulation, impurities in the particle delivery) and partly during operation (insects) [FIGURE 10]. In a new system a filter system with a bigger cross-section and better accessibility for maintenance should be foreseen.

No observations have been made during tests that indicated a general critical design problem of the technology. Some design solutions implemented in the current prototype showed the potential for further improvements. These ideas for the improvements will be realized in the next generation of the receiver.

FIGURE 5. Metallic mesh with lifted parts

FIGURE 6. Refurbished metallic mesh

FIGURE 7. Belt bucket elevator after dismantling

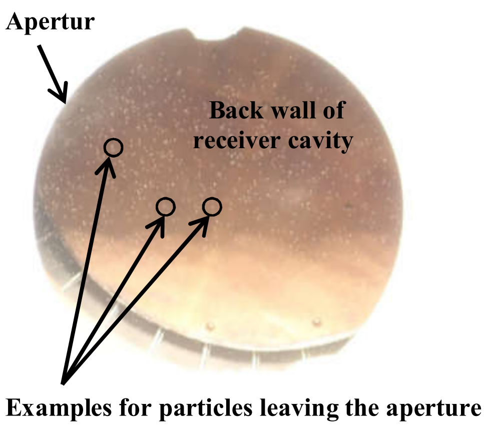


FIGURE 8. View into the receiver cavity towards the back wall of the cavity; particles leaving the aperture

FIGURE 9. Dust on bearing

FIGURE 10. Impurities in particles clogging a filter

SUMMARY AND OUTLOOK

A receiver prototype of the CentRec technology has been successfully tested on-sun in a closed particle loop system for nearly 70 h. Maximum average receiver outlet temperature of 965°C has been achieved. In the test period no major problem has been observed with the particle system. Several modifications and improvements on the system including an overhaul of a part of the receiver have been required during the tests. Experiences have been gained regarding particle flow behavior, overall system characteristics and measurement equipment. The test data and the evaluated performance will be used to validate a FEM model. With this model the thermal efficiency of a commercial design will be estimated.

The system has been dismantled. Further work in a national funded project starting in autumn 2018 will focus on the design for upscaling of the receiver and steam generator, particle backup heater, storage and transport system development and testing at a power level of 500 kW_{th}.

ACKNOWLEDGMENTS

The development of the CentRec technology was supported by the Helmholtz Validation Fund (grant no. HVF-0028) as well as by DLR Technology Marketing and DLR's Energy Programme Directorate (grant no. LRV 16/113). Part of the CentRec tests were co-funded and supported by the European Commission within the PEGASUS project under the Horizon 2020 Framework Programme of the European Union with grant agreement number 727540. The authors would also like to thank Gereon Feckler, Björn Freitag, Birgit Gobereit, Oliver Kaufhold, Andreas Krause, Martin Roeb, Christian Sattler, Hannes Stadler, Dennis Thomey, David Trebing, the operation team and all colleagues at the STJ for their valuable contribution to the project.

REFERENCES

1. Mark Mehos et al, “Concentrating Solar Power Gen3 Demonstration Roadmap”, Technical Report NREL/TP-5500-67464, January 2017
2. L. Amsbeck, B. Behrendt, T. Prosin, R. Buck, “Particle tower system with direct absorption centrifugal receiver for high temperature process heat”, Solarpaces 2014, Bejing, China
3. Sattler, Christian und Roeb, Martin und Agrafiotis, Christos und Thomey, Dennis (2017) Solar hydrogen production via sulphur based thermochemical water-splitting. Solar Energy, 156, Seiten 30-47. Elsevier. DOI: 10.1016/j.solener.2017.05.060 ISSN 0038-092X
4. Wei Wu, “A centrifugal Particle Receiver for HighTemperature Solar Applications”, PhD RWTH Aachen 2014, Logos Verlag Berlin 2015, ISBN 978-3-8325-3882-8
5. Ebert M., Amsbeck L., Jensch A., et al. Upscaling, Manufacturing and Test of a Centrifugal Particle Receiver. ASME. Energy Sustainability, V001T04A007. doi:10.1115/ES2016-59252.
6. Lars Amsbeck, Reiner Buck, Miriam Ebert, Birgit Gobereit, Johannes Hertel, Andrea Jensch, Jens Rheinländer, David Trebing, Ralf Uhlig, “First Tests of a Centrifugal Particle Receiver with a 1m² Aperture”, Solarpaces 2017, Santiago de Chile, Chile
7. DLR, The Juelich solar tower research facility, URL: http://www.dlr.de/sf/en/desktopdefault.aspx/tabid-8560/15527_read-44868/ (16.11.2017)
8. Ebert M., et al. „FIRST ON-SUN TESTS OF A CENTRIFUGAL PARTICLE RECEIVER SYSTEM”. ASME. Energy Sustainability 2018, to be published soon