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PEGASUS Centrifugal Particle Receiver CentRec300S - Optimization, Manufacturing and Test

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Abstract. The centrifugal particle receiver (CentRec®) developed by DLR for high-temperature solar applications, previously tested on sun in a 500 kWth prototype at the solar tower in Jülich was further developed and tested at slightly smaller scale of 300 kWth. The test with artificial sunlight provided more stationary and controllable boundary conditions. Outlet temperature of 681 °C was reached at an irradiating input power of 214 kW. The performance was determined with particle mass flow and temperature measurement systems. The data confirms the thermodynamic model for this receiver, indicating an extrapolated performance of 81% at nominal conditions.

Keywords: CSP, CentRec®, Particle Receiver, Direct Absorption Receiver, Experimental Test

1. Introduction

The CentRec® for high-temperature solar energy applications concept consists of a rotating, insulated hollow cylinder (cavity), with the axis inclined downwards from the solar tower into the heliostat field. Particles are fed into the receiver through a feeding cone at the top end of the cylinder (see Figure 1).

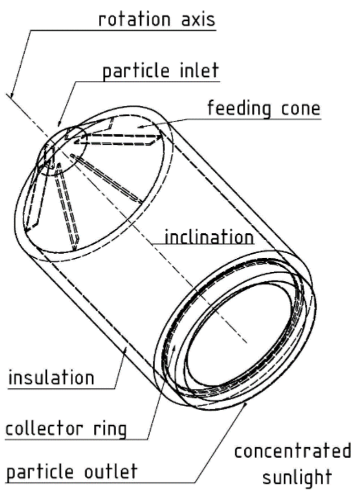

Figure 1. Scheme of the CentRec receiver [2]

The particles then travel downward along the inner cavity walls and exit the cavity at the lower end of the receiver drum. The downward motion of the particles from back to front of the receiver is determined by the superposition of centrifugal and gravitational forces. The residence time of the particles inside the cavity is controlled by the receiver rotational speed. Due to the rotation, the particles are pressed against the inside of the hollow cylinder. The particles form an optically dense particle film of several millimeters thickness that absorbs the incident solar radiation.

A 300 kWth receiver was developed and tested under steady-state conditions with artificial sunlight of DLR's Synlight facility in Jülich Germany within the framework of the PEGASUS project.

2. Test setup

The test setup is adapted to the characteristics of the Synlight facility (artificial sun in Jülich [8]), and the test platform has been prepared for the requirements of the test. While the CentRec300S receiver occupies one of the test chambers at Synlight, a second chamber holds the particle storage and cooling systems. The particles are heated with concentrated artificial sunlight from 149 xenon lamps and the peak flux up to 12.5 MW/m2 (Figure 2 and Figure 3).

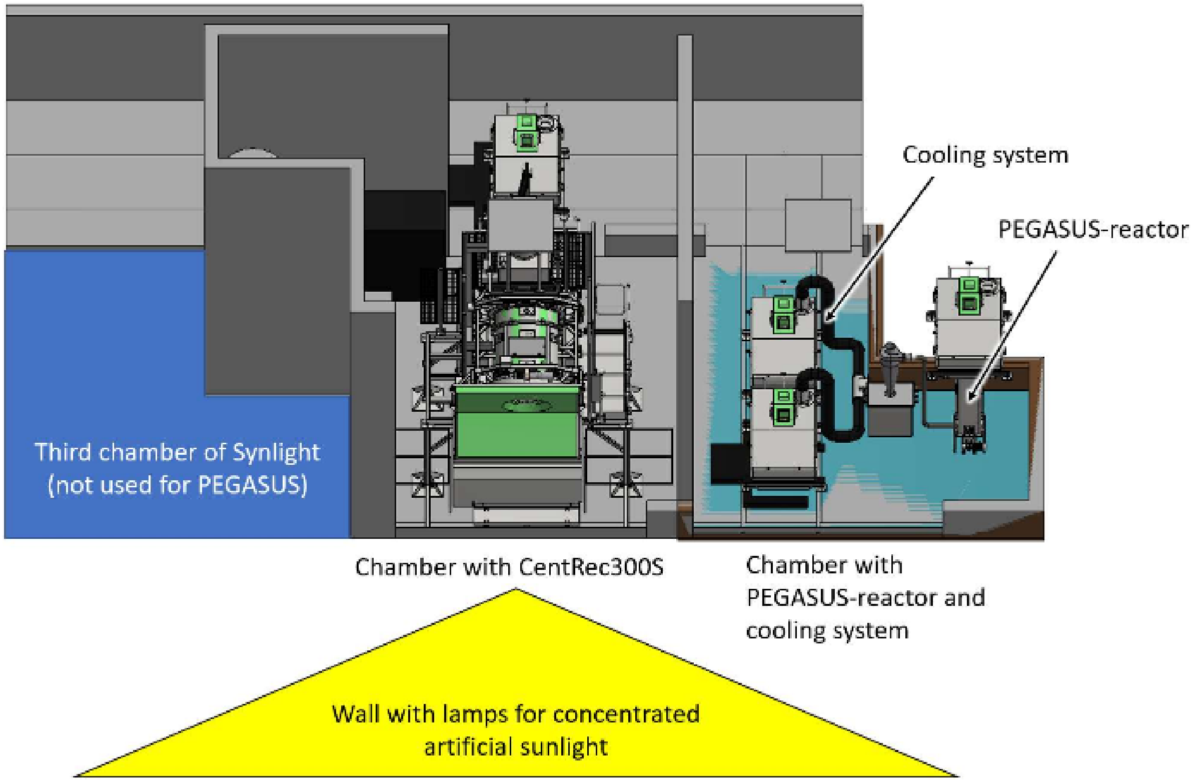

Figure 2. Overview installation of tests setup in Synlight facility

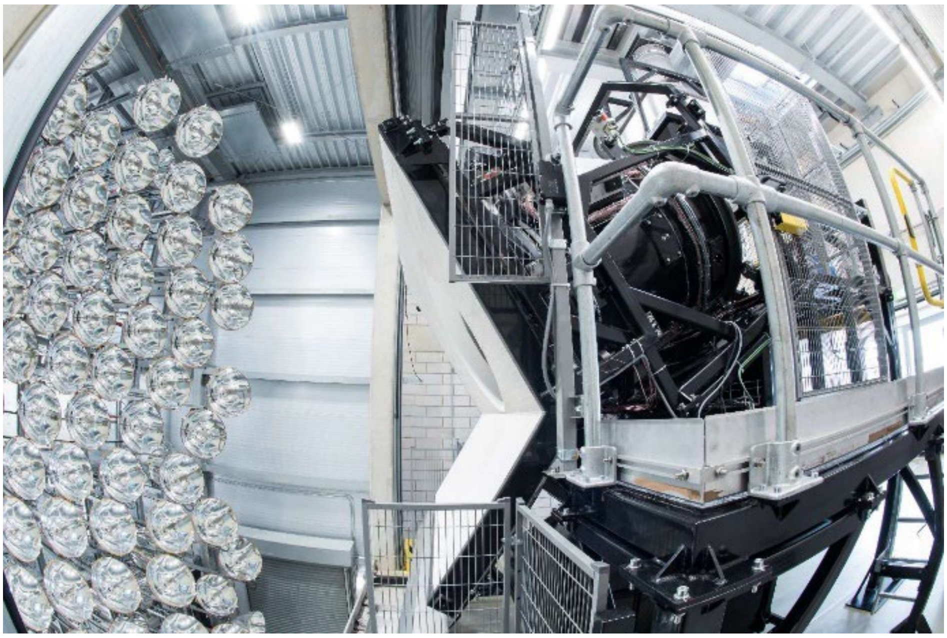

Figure 3. CentRec300S shown together with the Xenon lamps and the radiation shield (Synlight facility)

The test setup is shown in detail in Figure 4. The test rig used throughout the experimental campaign in Synlight facility consisted of:

- 3 transportable storages with cooling function (each with volume of 1t particles) on the floor
- Vacuum particle transportation system on the top for lifting cold particles from the cold storage with a mass flow of 1 kg/s
- Hopper below the transportation system with a particle mass flow measurement system
- Valve in the piping after the hopper, to start and stop the particle mass flow fed into the receiver
- Orifice plate as particle flow dosing unit (diameter 16.5 mm at 0.1 kg/s to 41 mm at 1.2 kg/s)
- Rotating CentRec300S receiver with an aperture diameter of 0.6 m
- Post-receiver piping to the hot storage with particle temperature measurement system

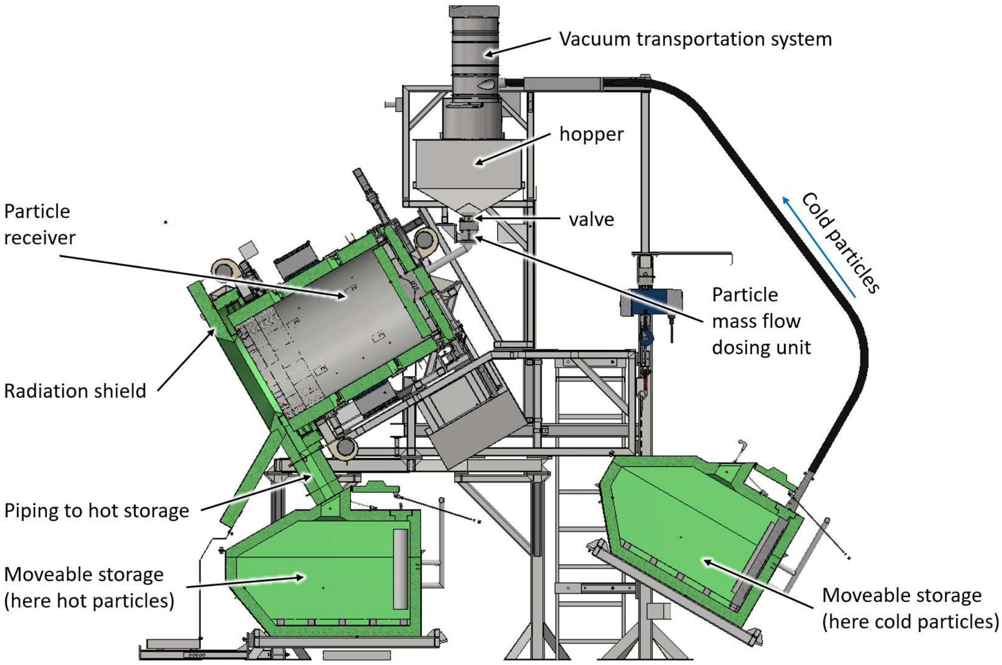

Figure 4. CentRec300S test rig with corresponding components for particle handling

3. Tests

The system is operated in batch mode because the particle loop is not designed for continuous operation. Up to 1 ton of cold particles was available per test. The associated testing time includes bringing the system into operation (establish a particle film in the receiver) and heating the system up to operational temperature and reaching thermal steady state conditions. Two operational concepts were tested during hot commissioning. Firstly, it was experimented with using one batch of particles to pre-heat the system, then during a rapid “pit-stop” remove the heated particles and provide a new batch of cold particles. The alternative concept was to provide a full particle film to the receiver and then freeze that film. That means the rotational speed is increased to a state in which all particles are pressed to the receiver walls and no axial movement of the particles takes place. In this “frozen” condition, radiation is then provided from a smaller number of Synlight lamps and the system is carefully heated to a constant temperature level. Then, the actual test with a moving particle film and the higher solar flux is started. It was found that the pit-stop could not be fast enough to avoid severe cool-down of the system. Therefore, the pit-stop routine was discarded.

To monitor the temperatures at the receiver, thermocouples have been installed along the receiver inliner (see Figure 5). This allows for monitoring the temperatures from the control room in real time. Figure 6 shows an example of a test day using the optimized test procedure determined during hot commissioning. The utilized operational settings corresponding to the test day plotted in Figure 6 are listed in the following table:

Table 1. Operational settings corresponding to the test day: 05-May-2020

Description	Value/Range	Unit
Power from lamps: 214 kW	214	[kW]
Maximum peak heat flux in aperture: 3811 kW/m²	3811	[kW/m^2]
Average heat flux in aperture: 829 kW/m²	829	[kW/m^2]
Particle mass flow: 0.26 kg/s	0.26	[kg/s]
Particle inlet temperature: 22 °C	22	[°C]

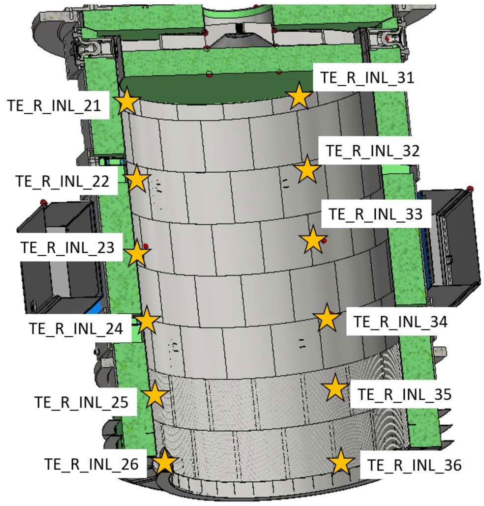

Figure 5. Position (yellow stars) of the inliner thermocouples (distributed in six different vertical levels along with four thermocouples at each level over circumference)

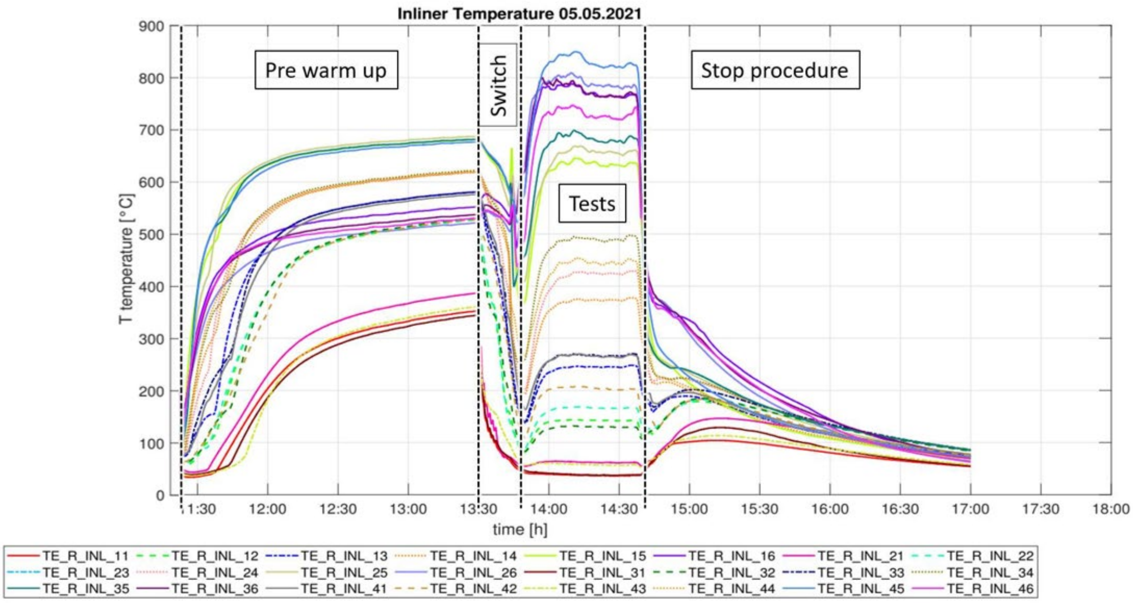

Figure 6. Inliner temperatures during the test day: 05-May-2020

One test day starts with a short preparation by moving the full cold and empty storages to the right position and performing a short inspection and checkup of the test rig. The first part of the test day includes the preheating of the receiver using a frozen particle film to reach steady state conditions. Once the temperatures become sufficiently stationary, the particle flow is activated and the power of the lamps is gradually increased in order to avoid higher temperature gradients. After reaching the maximum level of particles in the storage, the shutdown procedure is initiated by stopping the particle flow and gradually decreasing the power of the lamps.

4. Results

The daily tests were conducted using the PLC and LabView based control interface. At the end of each test day, gathered data was stored and the generated dataset was exported. These data can then be evaluated in more detail. For the purpose of continuous data evaluation during the PEGASUS project, a code was developed in Matlab with two execution modes:

1. Daily report – automated assessment of a test day from a set start time to a set end time,
2. Performance report – semi automated assessment of a test day to identify steady state (or near-steady state) conditions for later determination of receiver efficiency.

The evaluation of the performance plots for the frequently used particle mass flow rate allows drawing conclusions on the receiver performance (see Figure 7). The highest particle outlet temperature recorded was 681 °C with a total inlet beam power of 214 kW. In this test with particle flow of 0.26 kg/s, the receiver efficiency was 81%.

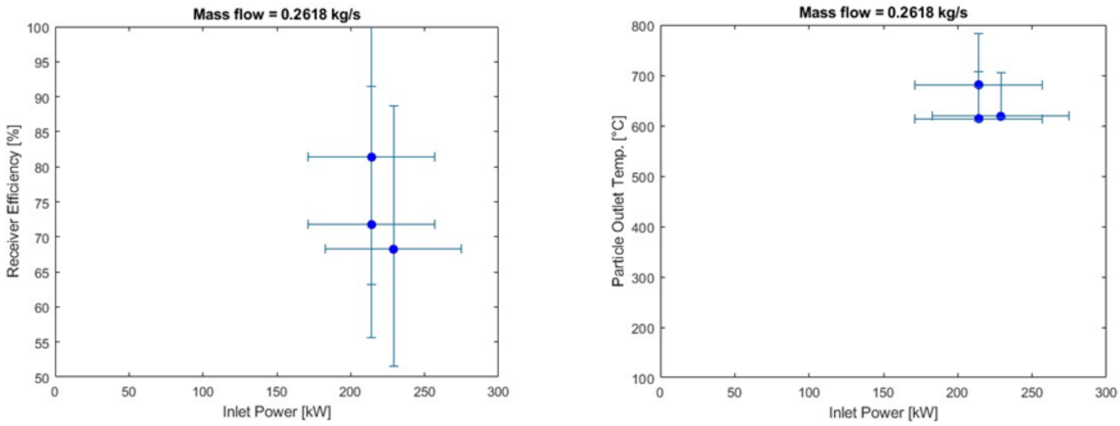

Figure 7. Receiver efficiency (left) and particle outlet temperature (right) as a function of the inlet power for different mass flows. For all plots, each data point represents the interpretation of the steady state results for a particular test day

Here, the receiver thermal efficiency is defined as follows:

$$\boldsymbol{\eta_{rec,th}} = \frac{P_p}{P_{inc}} = \frac{\dot{m}_p \cdot \bar{c}_{p,p} \cdot (T_{p,out} - T_{p,in})}{P_{inc}} \tag{1}$$

Where,

P_p: thermal power absorbed by the particles
P_{inc}: thermal power incident on the receiver
$\dot{m}_p$: mass flow of particles
$\bar{c}_{p,p}$: mean specific heat capacity of particles
$T_{p,out}$: outlet temperature of particles
$T_{p,in}$: inlet temperature of particles

The combined standard uncertainty of the receiver thermal efficiency according to the error propagation (GUM 1998 [5]) is the square root of the combined variance. Equation (2) is used to calculate the combined standard uncertainty of the receiver thermal efficiency:

$$\begin{aligned} U_c{}^2(\eta_{rec,th}) = {} & \left(\frac{\partial\eta_{rec,th}}{\partial\dot{m}_p}\right)^2 \cdot u^2(\dot{m}_p) + \left(\frac{\partial\eta_{rec,th}}{\partial\bar{c}_{p,p}}\right)^2 \cdot u^2(\bar{c}_{p,p}) + \left(\frac{\partial\eta_{rec,th}}{\partial T_{p,out}}\right)^2 \cdot u^2(T_{p,out}) \\ & + \left(\frac{\partial\eta_{rec,th}}{\partial T_{p,in}}\right)^2 \cdot u^2(T_{p,in}) + \left(\frac{\partial\eta_{rec,th}}{\partial P_{inc}}\right)^2 \cdot u^2(P_{inc}) \end{aligned} \tag{2}$$

To know which uncertainty source has the greatest influence on the combined uncertainty, the contribution of the individual uncertainties to the combined uncertainty, called the uncertainty index UI, is calculated according to the following equation

$$UI_i = 100 \cdot \frac{\left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i)}{{u_c}^2} \tag{3}$$

Figure 8 shows the contribution of each variable to the resulting thermal efficiency's combined uncertainty. The main sources of uncertainty are the values of incident power, specific heat capacity and the positive component of the particle outlet temperature.

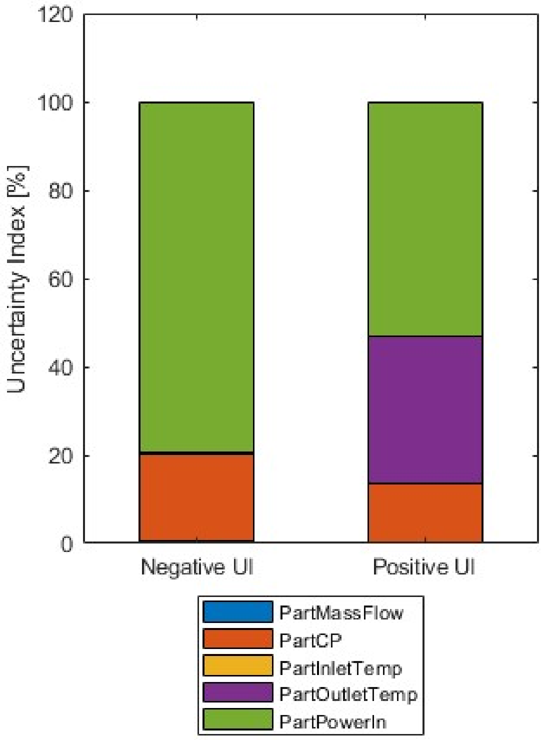

Figure 8. Uncertainty indices for a sample test day

Figure 9 shows an extrapolation of the receiver thermal efficiency for various levels of incident flux on the aperture, which was a simulation outcome for the preceding CentRec 500 test campaign on the Jülich solar tower [6]. The test data of the current tests were used to validate this simulation. A test day with the same inlet and outlet temperatures should be selected for this purpose. The test day 05-May-2021 meets these requirements with an average flux of 829 kW/m² and an efficiency of 81.4%. The calculated efficiency corresponds well to the extrapolated curve and the simulation results can therefore be validated.

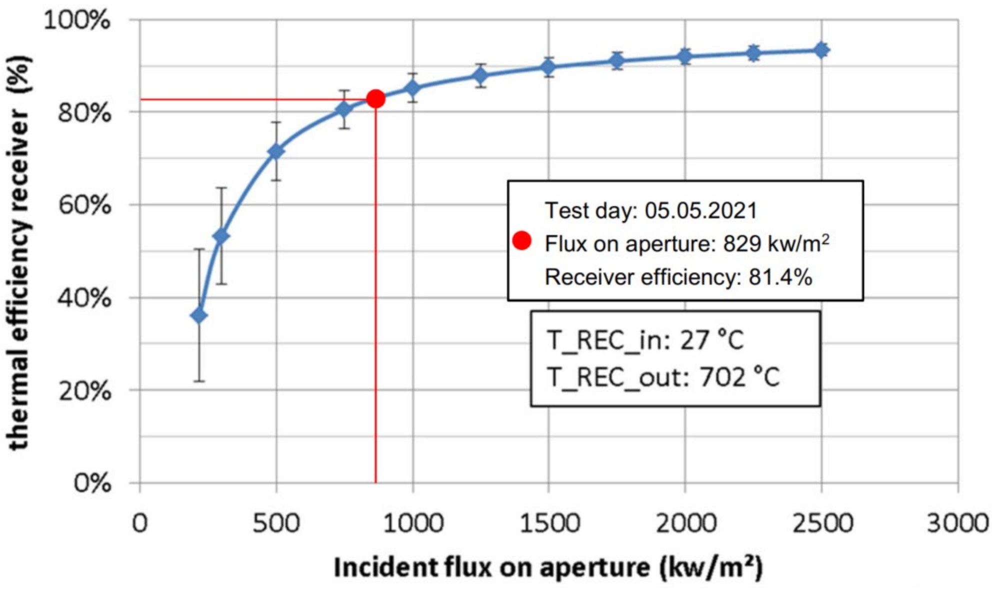

Figure 9. Expected receiver efficiency (blue) for higher incident solar flux on aperture, based on the measurements at 200 kW/m² on 20-June-2018. Red point corresponds to the test day on 05-May-2021 [6]

5. Summary and outlook

A receiver prototype of the CentRec® technology has been successfully designed, manufactured and tested with artificial sunlight in the DLR´s Synlight facility (artificial sun). An operational time of 64 hours with maximum average particle outlet temperature of 692 °C has been achieved. The test data have been evaluated with regards to local temperatures, mass flow and incoming power in order to calculate the overall receiver thermal efficiency. In order to quantify the quality of the measured data and the applied models, a comprehensive uncertainty analysis in accordance with GUM (JCGM 100:2008) was performed. The receiver efficiency of (81 ± 2.0) % has been deduced from the measurement data for part load operation with approximately 829 kW/m² incident radiation in the receiver aperture reaching a particle outlet temperature of 681 °C with maximum inliner temperature of 859 °C. As part of the HIFLEX [7] and HEHTRES (DLR test facility in Jülich) projects, the CentRec receiver will be integrated into a complete solar plant including tower and heliostat array and tested at higher irradiance levels and operating hours. For this purpose, the CentRec® receiver is planned to be further optimized, so that its performance in combination with the rest of the system can be evaluated.

Data availability statement

Supporting data available on request.

Underlying and related material

For more information regarding PEGASUS and HIFLEX project please visit the following links:

- Official website of the PEGASUS project “https://www.pegasus-project.eu”
- Official website of the HIFLEX project “http://hiflex-project.eu”

Author contributions

H. Barbri: conceptualization, investigation, writing, editing. **J. Rheinländer:** methodology, investigation, editing. **M. Ebert:** investigation, supervision. **M. Lubkoll:** investigation, editing. **D. Thomey:** supervision. **D. Laaber:** supervision. **L. Lackovic:** editing.

Competing interests

The authors declare no competing interests.

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