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# Experimental Investigation of a System of Two Vacuum Solar Receivers for the Continuous Reduction of Ceria Particles

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**Abstract.** A solar receiver for the continuous reduction of redox particles under vacuum conditions has been developed previously as part of a system to produce hydrogen from solar energy. Here, we report about a joint effort of Sandia and DLR to improve the receivers design and to demonstrate a system of two receivers with different vacuum pressures at DLR's solar simulator Synlight. We focus on the design and experimental investigation of three components: the novel beam down mirror, the novel secondary concentrator and the improved version of the particle conveying plate in the receiver. Irradiation test results and heat transfer analyses of the beam-down mirror and the secondary concentrator are being presented. The motion of the conveyor plate was improved by a MATLAB model, which predicts the transport speed of the particles on the conveyor.

**Keywords:** Hydrogen, Solarchemical Redox Cycle, Particles, Vacuum, Ceria, Secondary Concentrator, Beam Down, Concentrated Solar Energy

## 1. Introduction

In solar thermochemical redox cycles for fuel production, a metal oxide is first reduced with the help of concentrated solar energy and oxygen is released. Then it is oxidized by steam, carbon dioxide or both to produce hydrogen, carbon monoxide or a mixture of them. There are several concepts to realize this process, often using a metal oxide in form of foams or RPC structures [1]. Ermanoski et al. presented an alternative particle-based concept, which allows continuous operation, good heat transfer to the redox material and easy replacement of the redox material [2]. As another main feature, the reduction should take place in two solar reactors with different vacuum pressure levels, which is considered thermodynamically favorable. In a previous project, the concept was partly realized with one reduction reactor and hydrogen was generated [3,4]. Now, the design of the solar reduction reactors has been reviewed and design changes have been made. A two-reactor system to demonstrate a stable operation at different pressure levels is currently being erected. Its layout and some of its core components including their test results are presented here.

## 2. The system of two vacuum particle receivers

The two-receiver system currently being erected is depicted in Fig 1. In the particle feed chamber, 80 kg of ceria particles with a mean Sauter diameter of 277µm are preheated by resistive heaters to a temperature of 900°C, their assumed temperature after the oxidation reactor, which is not part of the experiment in this study. Driven by gravity, the particles flow to receiver 1, where their flow onto a horizontal motion conveyor is controlled by a linear actuator. The horizontal motion conveyor is a ceramic plate, which moves with a low forward acceleration and a high backward acceleration, causing a net forward motion of the particles due to consecutive sticking and sliding as described in more detail in [5]. The transportation speed and with it the particle film thickness on the plate is controlled by applying different acceleration profiles with a stepper motor. The particles reach the cavity, where they are heated to a temperature of 1450°C by concentrated radiation. Here, the radiation is created by DLR's solar simulator Synlight, redirected by a beam-down mirror and concentrated by a secondary concentrator within the receiver. The particles are being reduced, as a vacuum pressure of about 100-1000 Pa is being applied. The particles fall off the plate, pile up in a collection bin and fill the connection tube to receiver 2, creating a pressure separation [6,7]. Receiver 2 is identical to receiver 1, but a lower pressure of about 25 Pa is applied, so that the particles are reduced further. After leaving receiver 2, the particles are quenched by a water-cooled tungsten sheet and samples are collected for later thermogravimetric analysis to determine the reduction extent.

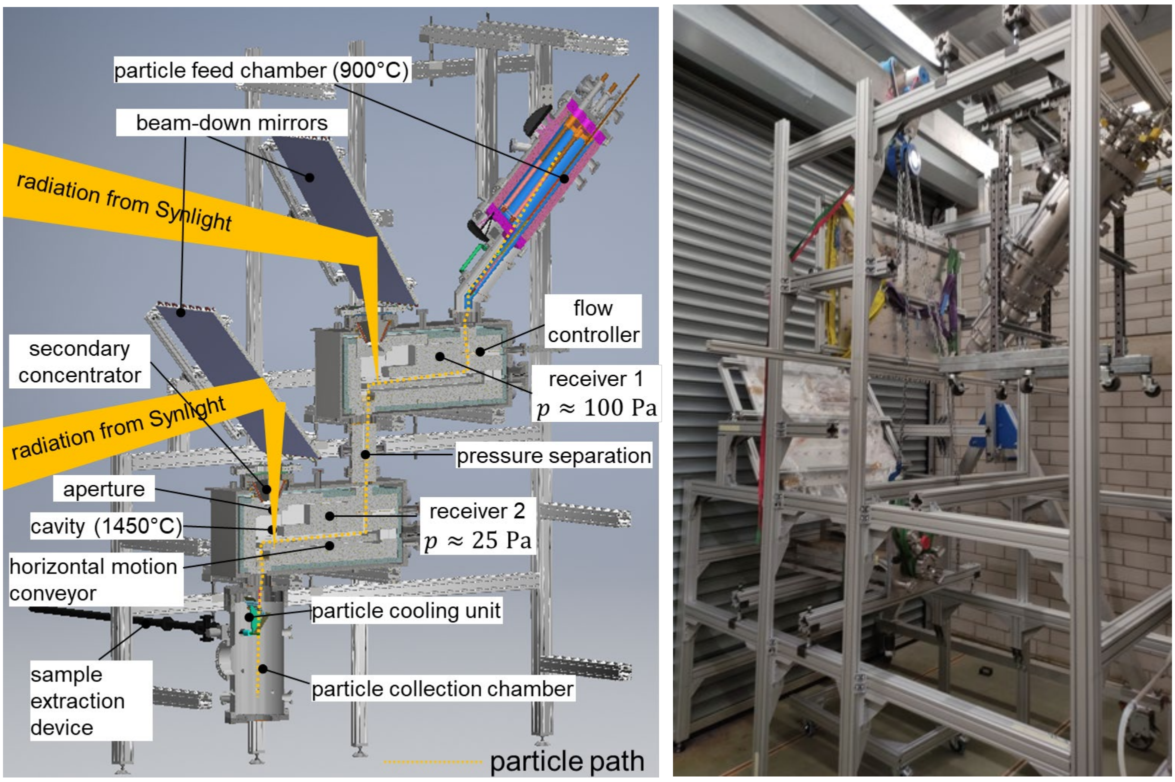


**Figure 1**. Two-receiver system for tests at DLR's solar simulator Synlight. Left: system to be erected, right: current state of the system.

Ultimately, the pressure separation between the two receivers and a more robust operation of the improved system should be demonstrated.

# 3. Preliminary results

So far, three new key components have been tested: the mirrors, the secondaries and the particle conveying plate. To design the optical components, a ray-tracing was performed. The results of the ray-tracing and of the component tests are described in the following.

## 3.1 Ray-tracing

To design the mirror and the window/aperture unit of the receiver, a ray-tracing study was conducted. Rays were generated by an OptiCAD model for Synlight [8] and were further traced and postprocessed in Python. Without using a secondary concentrator, 18 lamps were found to be necessary to deliver 5 kW power to the aperture of each receiver. Figure 2 shows the geometric arrangement of the lamps, the mirror and the aperture. Also, the resulting flux densities in the aperture plane and on the mirror are shown. About 90% of the radiation is not entering the aperture directly. This share is so large, because the scale of the receivers with their 6 cm aperture and power requirement of 5 kW is small for Synlight, which can deliver more than 300 kW of radiative power and has a focal length of 8 m. To capture a majority of the spillage, it was decided to design a secondary concentrator. The remaining spillage will be absorbed by a water-cooled disk to prevent uncontrolled reflection to the surroundings. While the flux density in the aperture plane shows peak values of 2 MW/m², the corresponding flux density on the mirror peaks at about 400 kW/m². By the use of the secondary concentrator the required number of lamps can be reduced to about 8, which lowers the thermal load on the components, mainly on the window and mirror. Also, the choice of lamps and their arrangement to irradiate the two receivers is more straightforward.

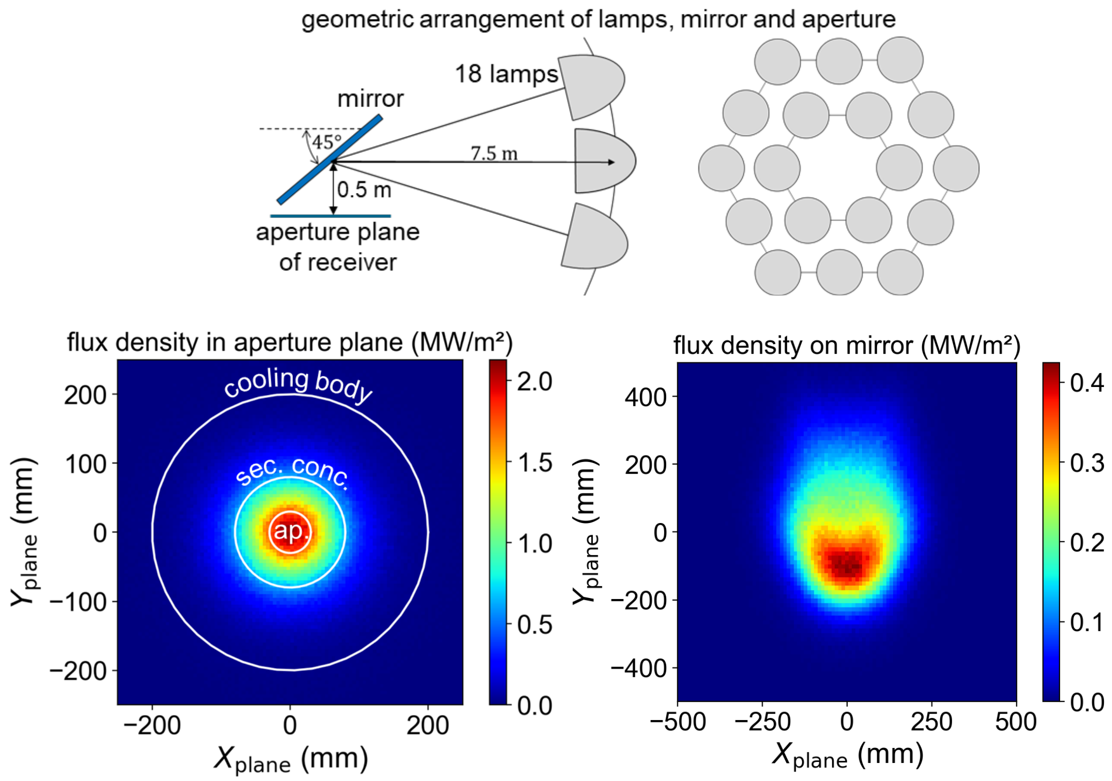


**Figure 2**. Flux density calculated by ray-tracing on the mirror and in the aperture plane when aiming at the center of the aperture with 18 lamps.

## 3.2 Construction and test of beam-down mirrors

To redirect the rather horizontal radiation of Synlight into the aperture, two beam-down mirrors with a dimension of 1m x 1m depicted in Fig. 3 were constructed. Their cross section is sketched in Fig. 4. The commercial reflector material Almeco VTS290 equipped with an adhesive layer resides on an aluminum substrate, which is connected by welded bolts to a water-cooled aluminum body. To reduce the contact resistance, a thin layer of thermal grease is applied between the cooling body and the aluminum substrate. Ten thermocouples are placed in this depth at lateral positions indicated in Fig. 5.

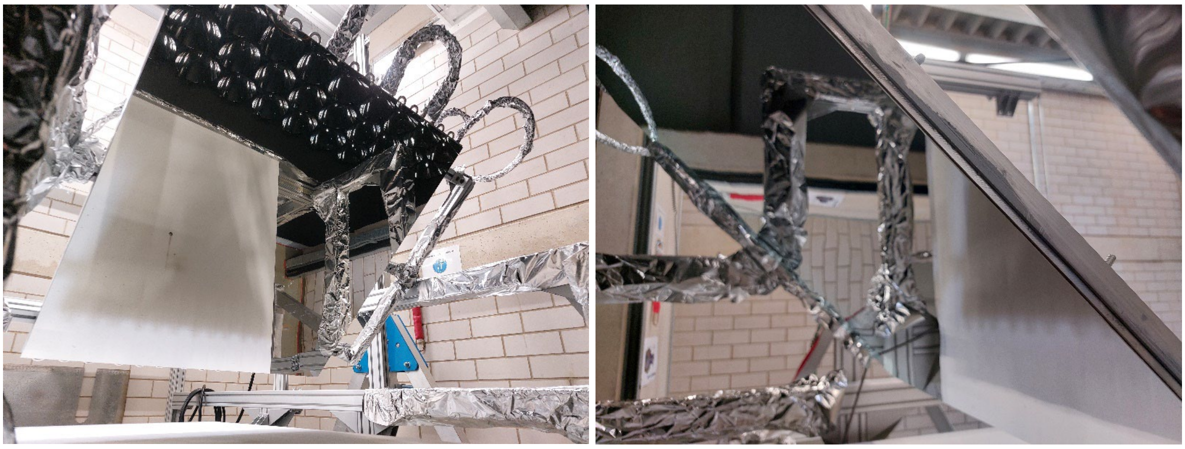

**Figure 3**. Beam-down mirror after the test.

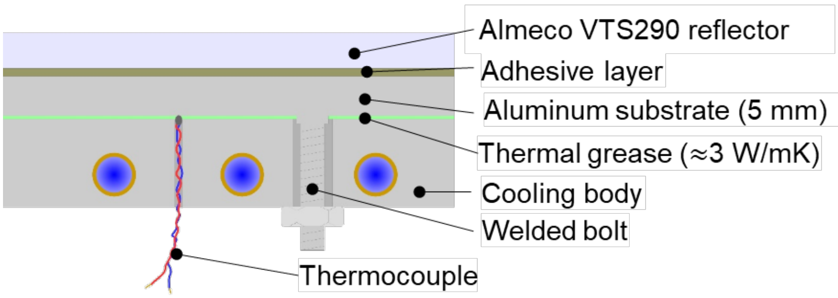


**Figure 4**. Cross sectional sketch of beam-down mirror.

One of the two mirrors was tested with 18 lamps of the simulator, corresponding to a radiative flux impinging on the mirror of 48.6 kW. The expected flux density distribution on the mirror coming from the lamps can be seen in Fig. 2. In addition to this, a part of the reflected radiation off a white target placed in the aperture plane hit the mirror as well. The view factor from the focal spot on the target to the mirror is 0.44, the reflectivity of the target is about 0.9 and the reflectivity of the mirror for light from the Synlight calculated by convoluting spectral data of the involved materials is about 0.85. Accordingly, radiation of about 16 kW is reflected back off the target on the mirror, so that in total about 65 kW of radiation hit the mirror. In the 65-minute-long steady-state period of the test, the cooling water entered the mirror at a mass flow of 4.81 l/min and at a temperature of 20.6°C. With an exit temperature of 50.3°C it rejected 9.86 kW of heat, which is a share of 15% of the total incoming radiation on the mirror. This agrees very well with the reflectivity calculated from the spectral manufacturer data before.

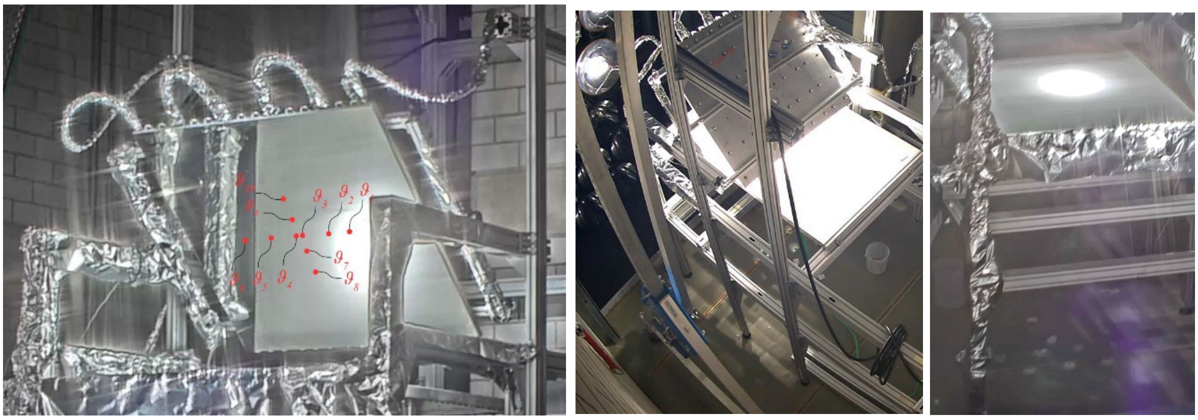

**Figure 5**. Beam-down mirror during test with indicated thermocouple positions.

After a total testing time of more than 2 hours, no visible damage or deformation of the mirror was observed. The peak front temperature was calculated from the thermocouple readings, from the peak flux density on the mirror and from the thermal resistances of the mirror's layers to be 104°C. This is well below the critical temperature of the adhesive of 150°C. Hence, it is concluded that the mirrors will be able to deliver the required power to the receivers without problems, in particular as the thermal load on them will be even lower if a secondary concentrator will be used.

## 3.3 Design and test of secondary concentrator

This secondary concentrator is designed to make use of the large spillage as described before. Also, it should help to cool the region between aperture and window, so that hot surfaces with large emission in the infrared regime to the window and the flanges are avoided.

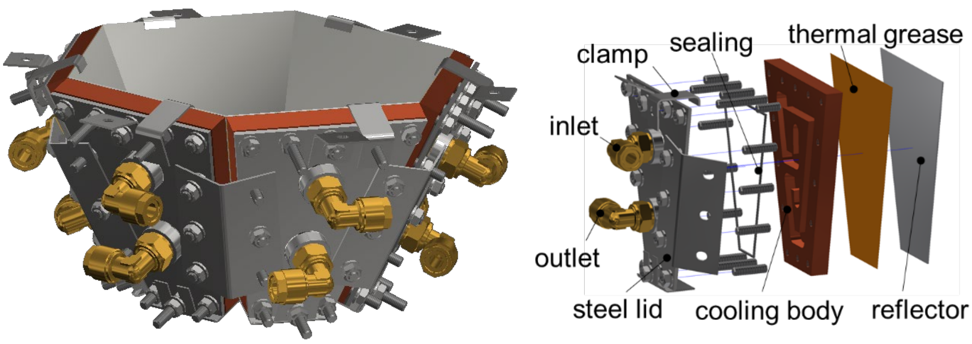


**Figure 6**. CAD design of the secondary concentrator.

The design of the secondary concentrator is depicted in Fig. 6. It consists of six segments. The same reflector material as for the mirror is used, but here the reflector material is directly attached to the cooling body by a clamp at the top and by a special thermal grease which can withstand temperatures of up to 400°C and is suited for vacuum conditions.

A first non-vacuum test with the new secondary concentrator and three lamps of the simulator was conducted, Fig. 7 shows the concentrator from the bottom, the top and while being irradiated during the experiment. The cavity of the receiver was heated to about 500°C and the secondary concentrator remained in good shape. Dust and volatile gases from insulation ascended from the cavity by natural convection. This will not happen in the planned vacuum tests, but limited the flux in the pre-tests as any damage under these off-design conditions needed to be avoided. Tests with higher fluxes will follow at vacuum conditions. Also, the insulation materials have been pre-fired meanwhile to prevent the emersion of volatile gases.

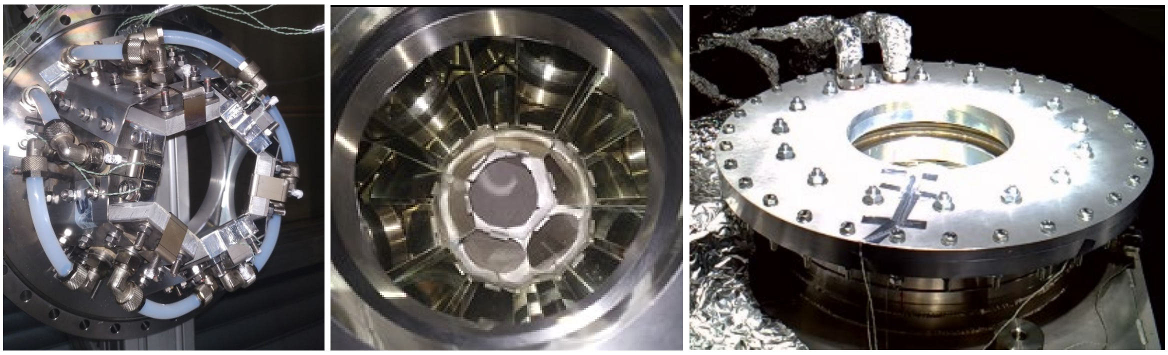

**Figure 7**. Secondary concentrator. Left: bottom view, middle: top view, right: during test.

## 3.4 Particle transport on the particle conveyor

To design a new drive mechanism for the particle conveyor, a model for the particle transport speed on it was developed in MATLAB. In the model, the particles are represented by a rigid body which either slides up the plate, down the plate or sticks to the plate as sketched in Fig. 8 (top and bottom left). Depending on the state, the rigid body is accelerated differently. To move the body forward, the plate needs to move forward with a low acceleration, so that the body sticks to the plate and is transported forward with it. Then, the backward motion needs to happen with a high acceleration, so that the plate slides back below the particles without carrying them too much with it. It is possible that particles are still in their forward motion while the plate makes the entire backward motion, but this not necessarily required; important is an overall net forward motion over an entire cycle of motion.

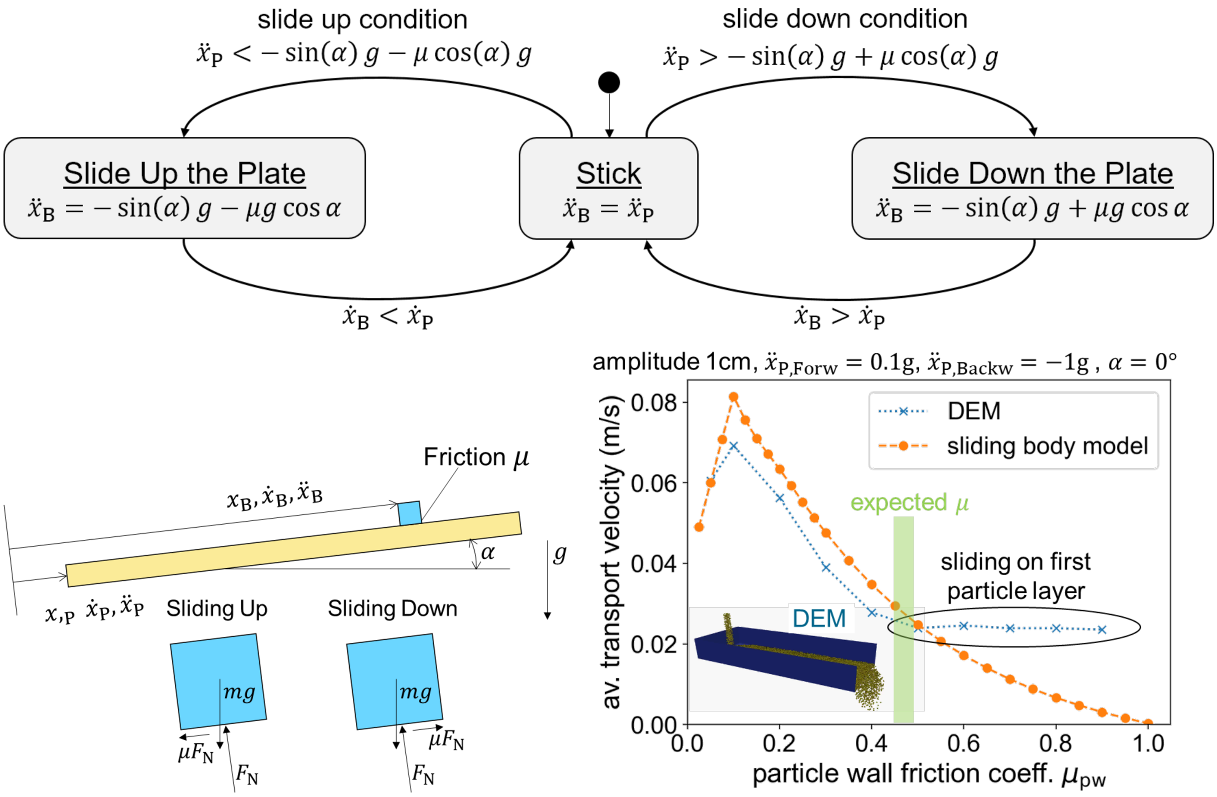


**Figure 8**. Model for transport speed on conveyor plate.

To check whether the rigid body model is valid, it was compared with DEM model results. Therefore, the Discrete Element Model (DEM) conveyor simulation setup from [5] was used with contact model parameters from the largest particles in the same study. Given the simplicity of the MATLAB model, the transport speed predictions agree well with the DEM model for various particle-wall friction coefficients, as it is shown in Fig. 8 (bottom right). For frictional values above 0.5, a detailed look at the DEM simulations revealed that a first layer of particles sticks to the plate, while the other particles still behave similar to a rigid body and slide above them. Then, the particle-particle friction is decisive for the transport speed for a given plate motion and the friction value in the rigid body model should be interpreted this way. It is concluded that the rigid body model is fast and accurate enough to predict the transport speed on the conveyor for design purposes. With the model, several plate motion profiles for different transport speeds were generated and can be selected to control the particle film thickness on the plate, as the mass flow arriving at the plate is regulated separately by a motor-driven ceramic slider with different sized orifices.

### 3.5 TGA test to mimic particle quenching before the sample collection

To be able to determine the reduction extent of the ceria particles after falling off the plate in the second receiver, a special sample extraction device was constructed to be able to collect several samples while maintaining vacuum conditions. To prevent re-oxidation of the samples, they need to be quenched fast enough. This should be ensured by the particle cooling unit in Fig.1. To estimate whether the particles would re-oxidize, the quenching was mimicked by a thermogravimetric analysis (TGA) test shown in Fig. 9. A 0.67 g sample of ceria particles is heated to a temperature of 1450°C with an argon purge gas flow of 100 Nml/min. A reduction extent of 0.027 is obtained. Then, they are cooled as quickly as the TGA device allows, which is significantly slower than expected in the later cooling device in the Synlight experiment, where a thin film of particles slides on a water-cooled tungsten plate. As the TGA results show insignificant re-oxidation in the next hour at ambient temperatures, it is also not expected to happen in the particle cooling and sample extraction unit in the Synlight tests.

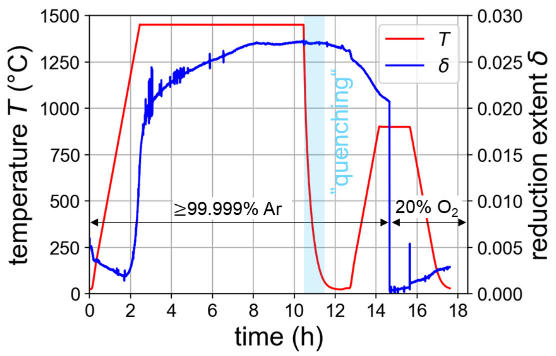


**Figure 9**. Thermogravimetric analysis to mimic particle quenching in cooling unit.

## 4. Conclusion and Outlook

The system in Fig. 1 has been partly erected and main components have been tested successfully. The beam-down mirror was irradiated with significantly more power than finally needed in the experiment without problems. The first test with the secondary concentrator was also successful, but dust and volatile gases ascended from the cavity by natural convection prevented tests at full power. These tests will follow at vacuum conditions and with pre-fired insulation material in the cavity. After erection of the full system and ensuring vacuum-tightness, the particle flow through the system and the pressure separation between the receivers will be investigated. In consecutive hot tests, the reduction extent of the particles will be measured and the efficiency of the system will be determined for various operating conditions.

## Data availability statement

Confidential data may be made available upon request. Underlying figure data and non-confidential data can be found in the supplemental material [9].

## Underlying and related material

Videos of the particle transport on the conveyor plate in the DEM model, a visualization of the motion predicted by the rigid body model and a collection of different plate and corresponding predicted particle motion profiles can be found in the supplemental material [9].

## Author contributions

According to the CreDIT guidelines, the contributions of the authors are listed:

- Johannes Grobbel: Conceptualization, formal analysis, writing – original draft, methodology, investigation, visualization, software, project administration
- Anthony McDaniel: Writing – review & editing, formal analysis, project administration, funding acquisition
- Ante Giljanovic: Formal analysis, investigation, visualization (secondary concentrator)
- Clarisse Lorreyte: Investigation, formal analysis (TGA)
- Jan Hendrik Müller: Investigation, formal analysis (mirror)
- Dennis Thomey: Project administration, funding acquisition
- Christian Sattler: Funding acquisition

## Competing interests

The authors declare no competing interests.

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