

DESIGN AND ON-SUN TESTING OF A SOLID PARTICLE RECEIVER PROTOTYPE

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ABSTRACT

A prototype direct absorption central receiver, called the solid particle receiver (SPR), was recently built and tested on-sun at Sandia National Laboratories. The SPR consists of a 6 m tall cavity through which a 1 m wide curtain of spherical ceramic particles is dropped and directly heated with concentrated solar energy. The focus of this current effort is to provide an experimental basis for the validation of computational models that have been created to support the development of the solid particle receiver as a solar interface for thermochemical hydrogen and solar power systems. In this paper we present detailed information on the design and construction of the receiver as well as test data including the temperature change of the particles and internal cavity walls. We conclude with a discussion of the steps needed to demonstrate the overall feasibility of the SPR concept.

INTRODUCTION

For the last several years Sandia National Laboratories (SNL) has been investigating solar interfaces appropriate for providing heat input to thermochemical fuel production processes [1-2]. Many of these processes require thermal energy to be input at a temperature in excess of 800 C [3-6]. In addition, the ability to provide this heat input around-the-clock is advantageous from an operational perspective and necessitates the use of thermal storage. The solid particle receiver (SPR) is a direct absorption central receiver concept initially conceived in the 1980's [7]. It utilizes a curtain of spherical ceramic particles that serve as both the heat transfer fluid (HTF) and thermal storage media [8]. The principle advantages of the SPR are 1) potentially high receiver efficiency due to direct absorption, 2) operational temperatures in excess of 1000 C, and 3) chemically benign solid HTF and storage media [9].

The initial SPR development efforts that took place in the 1980's resulted in a wealth of data related to the properties of solid particle HTFs [10] and thermal performance under idealized test conditions [11]. In addition, a computational model was developed based on the particle source in cell (PSI-CELL) approach that allowed for an estimation of receiver performance [12]. This model was validated with the experimental data that was available at the time, but which did not include on-sun testing of an open cavity receiver. Since then, additional models have been developed in collaboration with UNLV [13], NETL using MFIX [14], and most recently with researchers from DLR in Germany. The desired outcome of these modeling efforts is to both improve our understanding of the complex multiphase transport processes occurring within the receiver and to develop a simulation tool that may be used in the future design of commercial scale SPR systems. A necessary step in achieving this is to provide an appropriate experimental platform and use it to produce the experimental data needed to validate these models and establish confidence in their predictions.

RECEIVER DESIGN AND CONSTRUCTION

The prototype SPR was designed to be tested on top of Sandia's 61 m tall central receiver located at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM. The heliostat field at the NSTTF can provide an estimated 5 MW_{th} from 212 heliostats each with an area of 37 m². The optics of the field are such that ~75% of the concentrated flux can be intercepted by an aperture measuring 1.5 m in diameter. The receiver cavity itself measures 6.3 m in height by 1.85 m in width and 1.5 m in depth. Figure 1 shows front, side, and top views as well as the position of the particle curtain within the cavity and the illuminated length determined by the angles of the reflected sunlight from the front and back row heliostats.

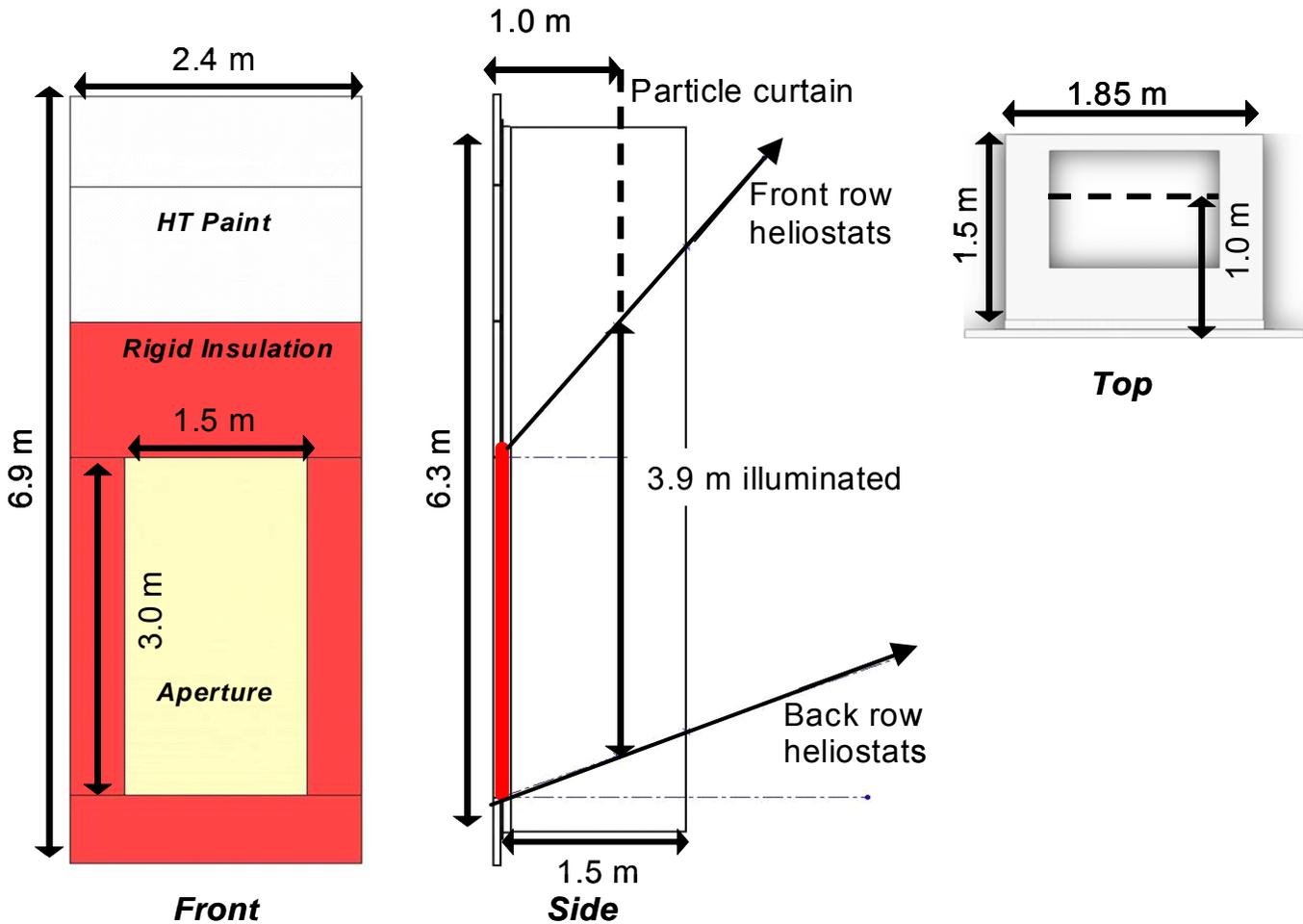


Figure 1. Projected views of the SPR cavity

The interior and front surface of the cavity bordering the aperture is covered with a 5 cm thick layer of Duraboard HD from Unifrax [15]. This material is a rigid alumina-silica insulation that can tolerate up to 1000 kW/m^2 once the organic binders have been baked out and melts at $1760 \text{ }^\circ\text{C}$. It is a relatively low cost option for rigid insulation compared with high-alumina products having higher flux tolerance.

The SPR currently operates in batch mode with a total particle inventory of roughly 1800 kg. The particles are commercially available from CarboCeramics and marketed as CARBO HSP 20/40. The cost in 2007 was less than $\$0.5/\text{lb}$. A listing of the properties of the particles is given in Table 1. These particles are very similar in composition to those used in the earlier solid particle receiver work that began in the 1980s. The estimated solar absorptivity is representative of previously measured values for these types of ceramics [16].

Depending on the flow rate, tests can run from roughly three minutes to just over seven minutes. The decision to run in batch mode was made primarily due to the thermal limits of the bucket elevator used to move the particles from the bottom of the receiver to the top. In this case, moving particles at a temperature greater than $170 \text{ }^\circ\text{C}$ would damage the elevator. In operation, particles are first loaded into the discharge hopper above the receiver cavity via the bucket

elevator. A sliding gate at the bottom of this hopper allows particles to drop through a machined slot that controls the flow

Table 1. Properties of CARBO HSP particles

Property	Value
Material composition	Aluminosilicate with $\sim 7\% \text{ Fe}_2\text{O}_3$
Median particle diameter	$697 \text{ } \mu\text{m}$
Specific gravity	3.56
Bulk density	2.0 g/cc
Roundness	0.9
Sphericity	0.9
Mean specific heat (0-300 $^\circ\text{C}$)	760 J/kg-K
Estimated solar absorptivity	0.85
Estimated thermal conductivity	2.0 W/m-K

rate over the $\sim 1 \text{ m}$ wide curtain. Previous studies have shown that a machined slot offers repeatable control over mass flow rate and that the rate does not change as the level of particles in

the hopper drops during discharge [17]. The particles fall through the open cavity where they are heated and finally collected in an internally insulated lower hopper. The curtain is uniform over the entire 1 m width. The thickness of the curtain does change as the particles continue to fall and spread out, but likely does not exceed 20 cm¹. A sliding gate on the lower hopper allows the particle flow to be metered into a fluidized cooler that lowers their temperature to within the limits of the bucket elevator. The major system components are shown in Figure 2.

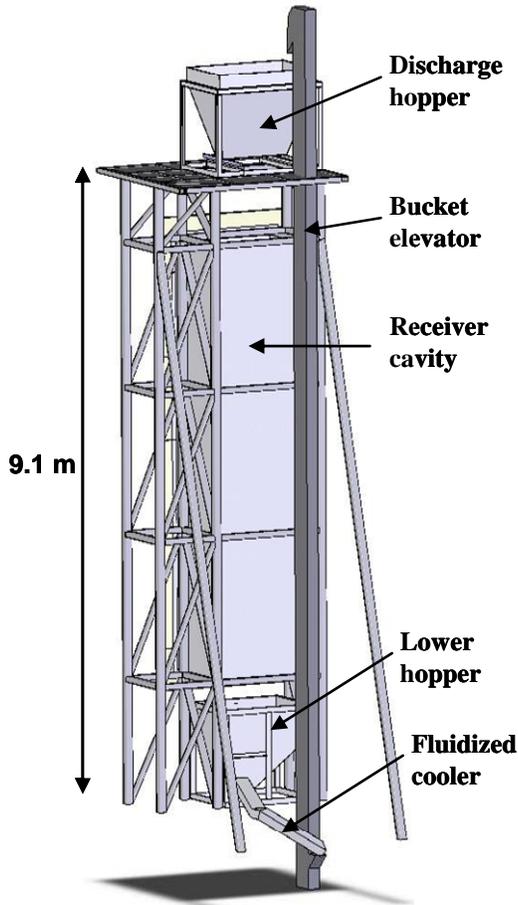


Figure 2. The SPR system layout

Data Acquisition

The receiver cavity was instrumented with Type K thermocouples (TCs) at several positions along the back and side walls. These TCs were installed just below the outer surface of the rigid insulation to avoid exposure to direct flux. Additional TCs were installed 15 cm above the insulation to measure the air temperature near the walls. These TCs were

¹ Thickness measurements taken using a smaller test platform indicate that the width of the curtain at flow rates consistent with this test was about 5 cm after the particles had fallen a total of 3 m.

only placed in areas within the cavity that did not see direct flux. Finally, the particle temperature at the discharge slot as well as at five vertical positions within the bottom hopper was also measured. A high speed camera (Phantom v7.1 @ 500 frames/second) was used to acquire on-sun images of the particles as they fell past the aperture. The particle image velocimetry (PIV) method was then used to calculate a velocity distribution from the set of images. Previous cold-flow testing had shown that after falling 3 m the particles are near their terminal velocity. We expect that the same is true of on-sun testing, although the terminal velocity might be slightly higher due to the reduced density of heated air.

Table 2. SPR test conditions

Date	DNI, W/m ²	Flow rate, kg/s-m	Input power, MW
2-8-08	1050	8.72	1.90
2-8-08	1070	8.72	2.28
2-11-08	1002	5.32	1.52
2-11-08	1038	5.32	2.28
2-11-08	1040	3.84	2.28
2-13-08	1050	3.84	1.52
2-18-08	1000	8.72	2.56
2-22-08	962	5.32	2.56
2-28-08	953	3.84	2.56

EXPERIMENTAL RESULTS AND DISCUSSION

Testing was conducted in January and February of 2008. In Albuquerque, during this time of year, the levels of direct normal insolation (DNI) are typically above 1040 W/m² sometimes reaching 1080 W/m². All tests were done with a single aimpoint in the center of the aperture. The heliostats used for testing were concentrated in the center of the field to maximize intercept. The maximum number of heliostats used in a test was set at 140, roughly 65% of the field. Analysis indicated that above this level the spillage on the back wall would exceed 1000 kW/m² and result in damage to the cavity insulation. The test plan called for running three particle flow rates at three flux levels and is summarized in Table 2².

The amount of power entering the aperture is estimated using the code DELSOL [18]. Parameters within the code have been adjusted, based on experimental data, so that the output is an accurate prediction of the performance of the field at the NSTTF. The data were taken using a flux imaging

² The mass flow rates in Table 2 are given per unit width of the curtain, which was 0.98 m.

system combined with a single point flux measurement taken with a Kendall radiometer. The flux image was scaled using the radiometer output and the resultant flux profile used to adjust the output from DELSOL.

The temperature increase (ΔT) of the particles during on-sun testing ranged from 100 °C to nearly 250 °C for a single pass through the cavity. These data are summarized in Figure 3.

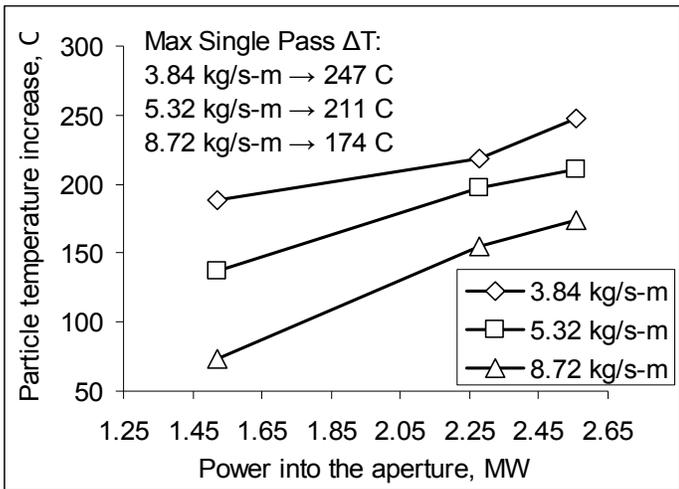


Figure 3. Single pass temperature rise of the particles

In general, for a given amount of power the temperature change of the particles increases as the flow rate is reduced. This is primarily a result of decreased particle shading i.e. a lower density curtain allows each particle to receive more direct flux. The increased temperature rise comes at the expense of absorption efficiency, Figure 4, since at low flow rates a larger relative fraction of the incident energy strikes the back wall as opposed to the particles, violating a cardinal rule of receiver design which is to “put the flux on the absorber”. The receiver efficiency was calculated by dividing the energy gain of the particles by the amount of energy

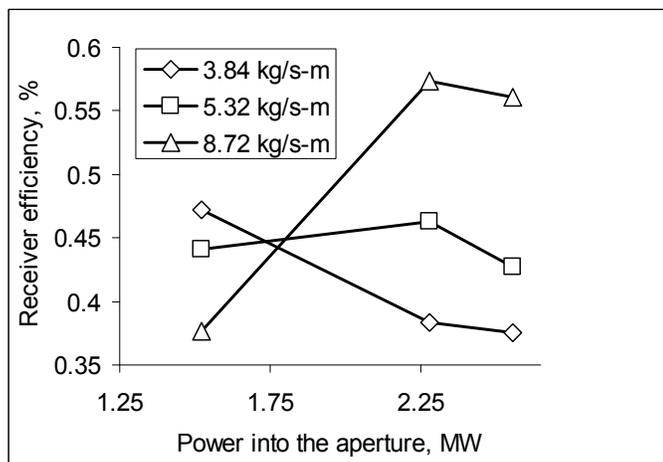


Figure 4. Calculated receiver efficiency. In general, increasing the flow rate improves efficiency as the curtain is more opaque and intercepts a greater fraction of the incoming solar energy.

entering the aperture as estimated by DELSOL. The calculation does not take into consideration the negative impact on efficiency of flux spillage i.e., energy striking the receiver that does not intercept the aperture. Additionally, this prototype receiver did not operate at the higher flux levels (increase efficiency) or temperature (decrease efficiency) required for a commercial device.

Data for peak back wall temperature are shown in Figure 5. An image of SPR aperture during on-sun testing is shown in Figure 6 and illustrates the difference in curtain transparency at the three flow rates.

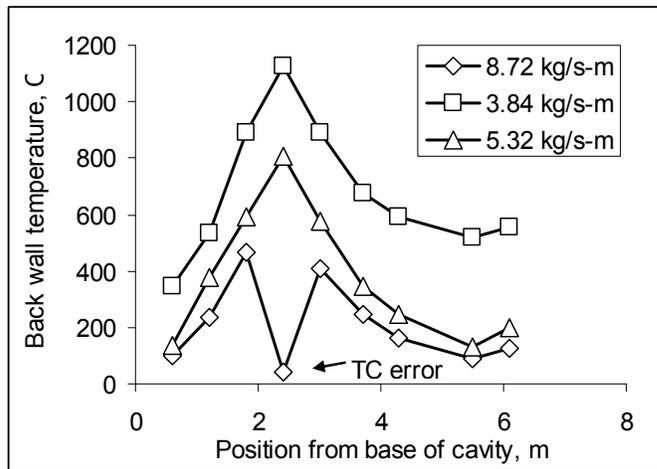


Figure 5. The temperature distribution along the back wall of the receiver cavity

Excessive heating of the back wall can be problematic

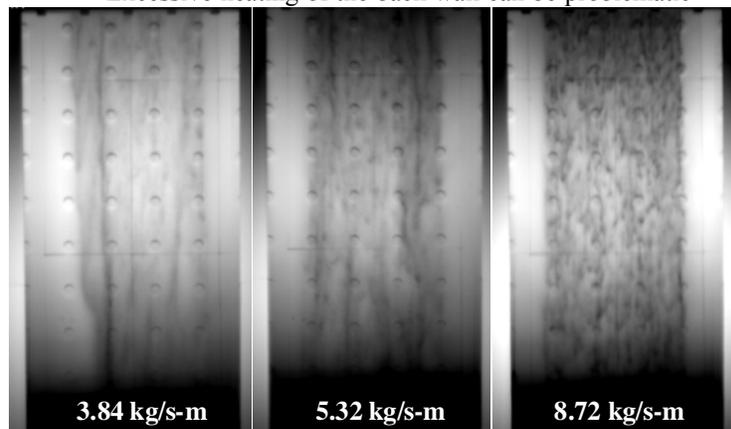


Figure 6. The particle curtain as it passes through the aperture. Wind is disturbing the curtain at the bottom-left corner of the 3.84 kg/s-m case.

with respect to the cavity insulation. The Duraboard HD used during these tests is tolerant to flux up to 1000 kW/m². We observed the formation of substantial cracks through the insulation board in the vicinity of the region of peak

temperature shown in Fig. 5. Although it is unlikely that flux on the back wall ever exceeded 1000 kW/m^2 , it is possible that cycling of the back wall temperature combined with rapid heating and water deposited in the cavity during storms caused the degradation. Research on more durable cavity insulation materials is merited since, in a commercial device, the frequent replacement of the insulation within the cavity is likely to be an unacceptable O&M cost. Additionally, heating rates can be moderated to reduce thermal stresses. During testing, the general procedure called for first initiating the particle flow and then bringing all of the heliostats to target within a time span of five minutes. One concern prior to testing on-sun was the potential impact on curtain stability of buoyancy driven flow within the cavity. Although the particles are dense and acquire a relatively large amount of momentum as they fall there is a chance that air currents could be set up within the cavity that would disturb the uniformity of the particle curtain. We did not observe this during testing even though the air within the cavity achieved temperatures in excess of 800°C , through contact with the hot cavity walls.

A related concern is the impact of ambient wind on the particle flow within the open cavity receiver. In commercial scale systems, the receiver cavity might be located 250 m or more above the ground and exposed to almost constant winds. We measured wind speed at the aperture prior to most tests. The maximum measured wind speed was in excess of 13 m/s, with most tests conducted when winds exceeded 5m/s. In most cases the wind came either directly out of the north or the south and had little effect on the curtain regardless of speed. Winds that were not directly normal to the aperture did produce some instability in the curtain. This observation is consistent with some of the qualitative predictions of our computational models and is evidence enough that we should analyze this affect further and develop mitigation strategies.

CONCLUSIONS AND FUTURE RESEARCH

The on-sun test program concluded in March of 2008 provided a foundational data set for the validation of existing and future computational models. The demonstration of a single pass temperature increase in excess of 200°C at practical particle mass flow rates is an encouraging result, as is the relative stability of the curtain when exposed to wind and buoyant flows. We are, however, reluctant to say that the overall feasibility of the concept has been sufficiently demonstrated. That will involve achieving four primary milestones:

1. The demonstration of a particle exit temperature in excess of 900°C . This is the temperature required to produce hydrogen with sulfuric-acid-cracking cycles. To achieve 900°C we must optimize the optical design of the receiver. For example, in the current test the average flux on the particle curtain was 400 suns. Our performance models indicate that an 800 sun average

will be required to achieve 900°C given an inlet temperature of 600°C . Achieving 900°C may also require recirculation of the particles to increase residence time for a receiver of the size that we're likely to test. In larger systems having a greater drop distance recirculation may not be necessary.

2. The demonstration of receiver efficiency in excess of 70% (heat absorbed/power into aperture). This can be achieved by increasing the average flux on the curtain by increasing the incident power (only half of our field was used in these tests) and reducing the unheated length of the curtain. It is also likely that using smaller particles would improve efficiency.
3. The development of a rigorous multi-phase analysis of the impact of ambient wind on curtain stability in an open cavity and the demonstration of strategies to mitigate this issue.
4. The demonstration of the physical stability of the particles i.e. that particle attrition due to self abrasion is within acceptable limits for economical plant operation.

Achieving these milestones will require a mix of computational and experimental efforts. We currently plan to proceed with the validation of existing computational models using the data collected in the initial test program and then to design an optimized cavity receiver based on our current test platform and suitable for use at the NSTTF with our entire field, rated at over 4 MW_{th} . This receiver will incorporate a high temperature bucket lift and enable hot particle recirculation. Assuming that the four milestones can be achieved, the next step is to proceed with scale-up and balance of plant design with an eye towards the eventual demonstration of an integrated solar hydrogen system, likely based on the hybrid sulfur (HyS) cycle.

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