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Highlights of the High-Temperature Falling Particle Receiver Project: 2012 - 2016

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Abstract. A 1 MW_t continuously recirculating falling particle receiver has been demonstrated at Sandia National Laboratories. Free-fall and obstructed-flow receiver designs were tested with particle mass flow rates of ~1 – 7 kg/s and average irradiances up to 1,000 suns. Average particle outlet temperatures exceeded 700 °C for the free-fall tests and reached nearly 800 °C for the obstructed-flow tests, with peak particle temperatures exceeding 900 °C. High particle heating rates of ~50 to 200 °C per meter of illuminated drop length were achieved for the free-fall tests with mass flow rates ranging from 1 – 7 kg/s and for average irradiances up to ~ 700 kW/m^2. Higher temperatures were achieved at the lower particle mass flow rates due to less shading. The obstructed-flow design yielded particle heating rates over 300 °C per meter of illuminated drop length for mass flow rates of 1 – 3 kg/s for irradiances up to ~1,000 kW/m^2. The thermal efficiency was determined to be ~60 – 70% for the free-falling particle tests and up to ~80% for the obstructed-flow tests. Challenges encountered during the tests include particle attrition and particle loss through the aperture, reduced particle mass flow rates at high temperatures due to slot aperture narrowing and increased friction, and deterioration of the obstructed-flow structures due to wear and oxidation. Computational models were validated using the test data and will be used in future studies to design receiver configurations that can increase the thermal efficiency.

INTRODUCTION

High-temperature falling particle receivers are being pursued to enable higher efficiency, next-generation power cycles operating at >700 °C for concentrating solar power (CSP). Unlike conventional solar thermal receivers that employ fluids flowing through panels of irradiated tubes, which increases thermal resistance and solar flux restrictions, particle receivers heat the particles directly, enabling direct storage and higher solar concentrations that lead to higher temperatures and efficiencies and lower costs [1]. Conventional central receiver technologies employing molten salts are limited to temperatures of around 600 °C. At higher temperatures, nitrate salt fluids become chemically unstable [2]. In contrast, receivers using solid particles that fall through a beam of concentrated solar radiation for direct heat absorption and storage have the potential to increase the maximum temperature of the heat-transfer media to over 1,000°C [3]. Once heated, the particles may be stored in an insulated tank and/or used to heat a secondary working fluid (e.g., steam, CO_2, air) for the power cycle. Thermal energy storage costs can be reduced by directly storing heat at higher temperatures in a relatively inexpensive medium (i.e., sand-like particles). Because the solar energy is directly absorbed in the sand-like working fluid, the flux limitations associated with tubular central receivers (high stresses resulting from the containment of high temperature, high pressure fluids) are mitigated. The falling particle receiver appears well-suited for scalability ranging from 10 – 100 MWe power-tower systems [3].

Although a number of analytical and laboratory studies had been performed on the falling particle receiver prior to this study [4-14], only one set of on-sun tests of a simple falling particle receiver had been performed [15]. Those tests only achieved 50% thermal efficiency, and the maximum particle temperature was less than 300°C. Kolb [16] and Tan et al. [17-20] discuss the use of air recirculation and aerowindows to mitigate heat loss and wind impacts in falling particle receivers, but no tests were performed. Hruby [8] introduced the concept of using ceramic objects or plates in the particle flow stream to decelerate the particles for increased heating, but no studies were conducted. This study addresses the gaps and needs identified in the previous studies.

The objective of current work was to advance falling particle receiver designs for concentrating solar power applications that will enable higher temperatures (>700 °C) and greater power-cycle efficiencies (≥50% thermal-to-electric). This paper presents highlights from a project funded by the United States Department of Energy (2012 – 2016) that demonstrated the world's first 1 MW_t continuously recirculating falling particle receiver system operating at over 700 °C particle outlet temperatures at particle mass flow rates ranging from 1 – 7 kg/s (Figure 1).

Figure 1. Images of 1 MW_t particle-receiver system tested at Sandia National Laboratories.

PARTICLE RECEIVER SYSTEM

The falling particle receiver is a simple system that directly heats ceramic particles using concentrated sunlight. The 1 MW_t receiver system consists of a 2 m x 2 m x 2 m cubical cavity receiver (through which particles fall) with a 1 m^2 aperture, a collection hopper, a particle lift to carry the particles back to the top of the receiver, and a top hopper that holds and releases particles into the receiver (Figure 2) [21]. Aside from the particle lift, the entire process is based on gravity-driven flow of the particles through each component, reducing parasitic power consumption.

Two different receiver designs were tested: free-fall and obstructed flow (Figure 3). The free-fall design is the simplest to implement, but particles can accelerate rapidly, reducing the residence time in the concentrated beam of sunlight and dispersing the particles. Porous obstructions using a staggered array of mesh structures were also designed and tested to slow the particles and increase the residence time. Challenges associated with the mesh include wear and deterioration at high irradiances with particle abrasion [21]. However, the mesh structures were effective at reducing the particle velocity by an order of magnitude and slowing the terminal velocities to ~0.5 m/s, which provided additional particle flow stability and opacity relative to free-fall.

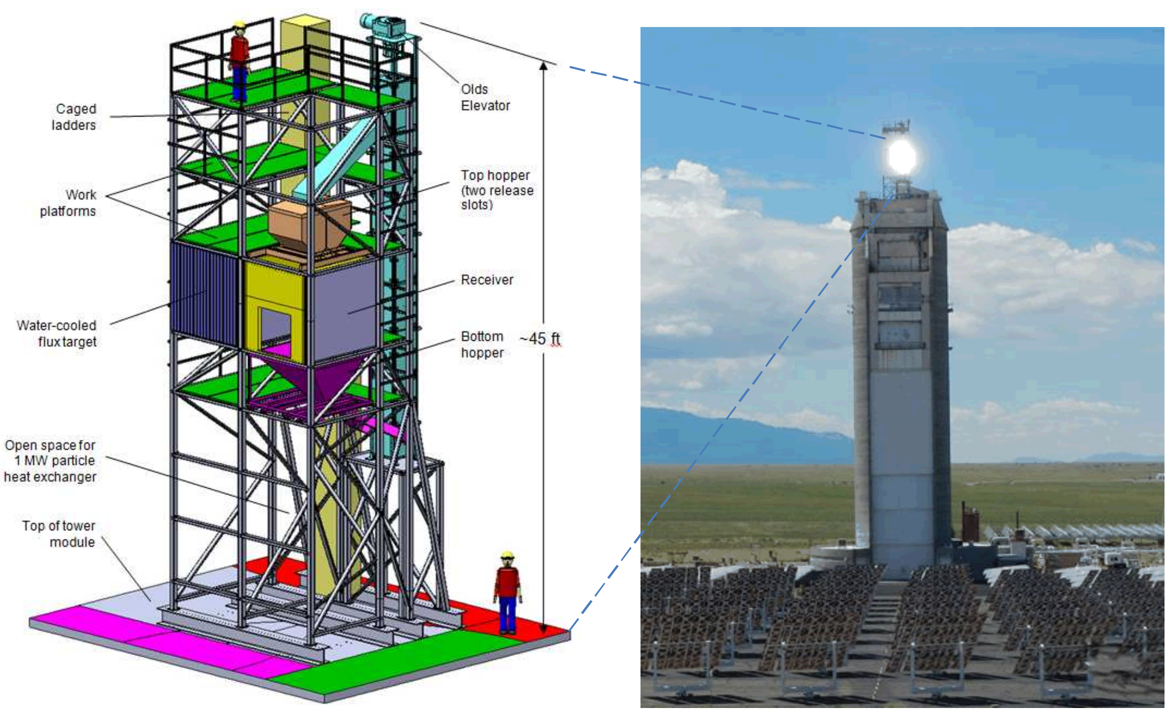

Figure 2. On-sun falling particle receiver prototype system.

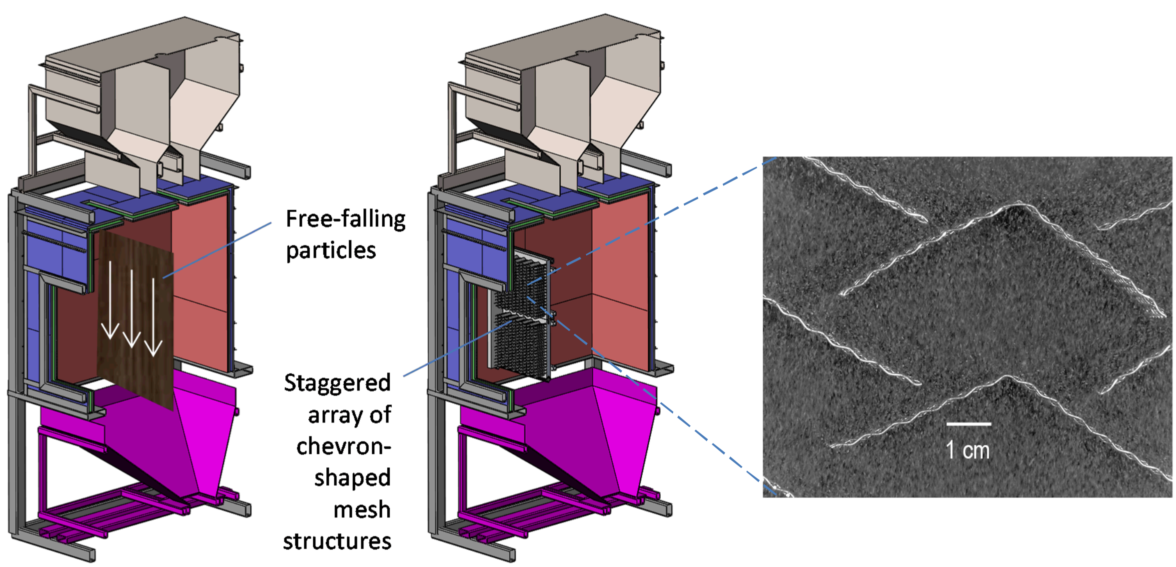

Figure 3. Cutaway illustration of free-falling (left) and obstructed-flow (middle and right) particle receiver designs.

On-sun testing of the free-fall particle receiver design showed that the particle temperatures increased by 50 to 200 °C per meter of illuminated drop length for mass flow rates ranging from 1 – 7 kg/s per meter of particle-curtain width and for average irradiances up to ~ 700 kW/m^2 (Figure 4). Higher temperatures were achieved at the lower particle mass flow rates due to less shading. The obstructed flow design yielded particle temperature increases over 300 °C per meter of illuminated drop length for mass flow rates of 1 – 3 kg/s per meter of curtain width for irradiances up to ~1,000 kW/m^2 (Figure 5). Peak particle temperatures greater than 900 °C were achieved with bulk particle outlet temperatures reaching nearly 800 °C.

The calculated thermal efficiencies were quite variable due to uncertainties in the particle mass flow rates at high temperatures, which caused narrowing of the discharge plate aperture and additional friction between the particles and walls. At particle outlet temperatures >700 °C, the estimated thermal efficiencies of the obstructed flow design reached up to ~80% at particle mass flow rates of 1 – 2 kg/s, while the thermal efficiencies of the free-fall design reached up to ~60 – 70% at particle mass flow rates of ~5 kg/s (Figure 4 - Figure 6). Test results were used to validate computational models of the falling particle receiver performance at different mass flow rates, solar irradiances, and particle temperatures. A rank-regression analysis of the simulated free-fall tests showed that the particle temperature rise was most impacted by the incident power (positive correlation), inlet particle temperature (negative correlation), and particle mass flow rate (negative correlation). The simulated thermal efficiency was most impacted by the particle mass flow rate (positive correlation) and particle inlet temperature (negative correlation). At larger scales (≥10 MW_e) and higher irradiances (1000 – 2000 suns), thermal efficiencies approaching 90% are expected based on modeling results.

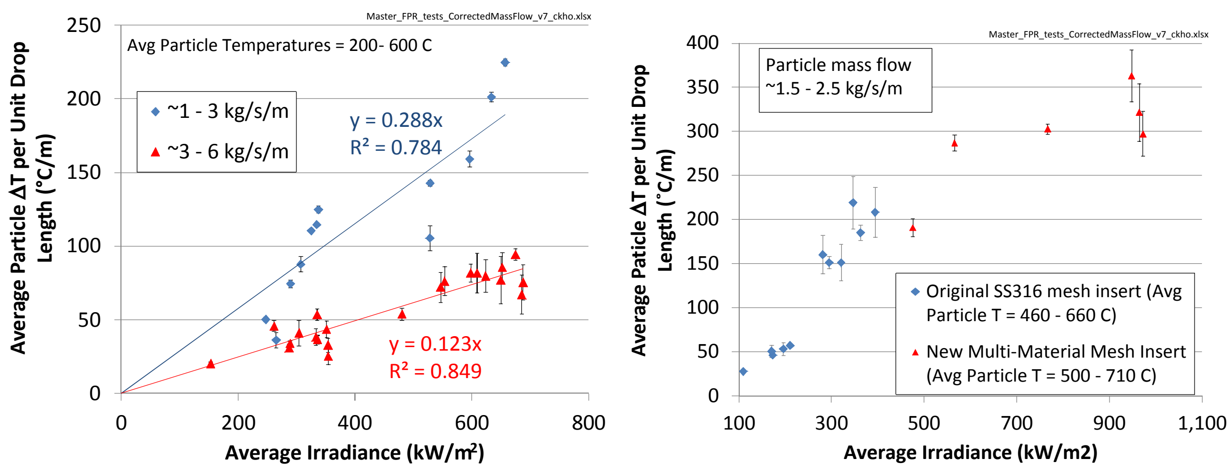

Figure 4. Measured particle temperature rise for free-fall (left) and obstructed-flow (right) receiver tests. Error bars represent one standard deviation.

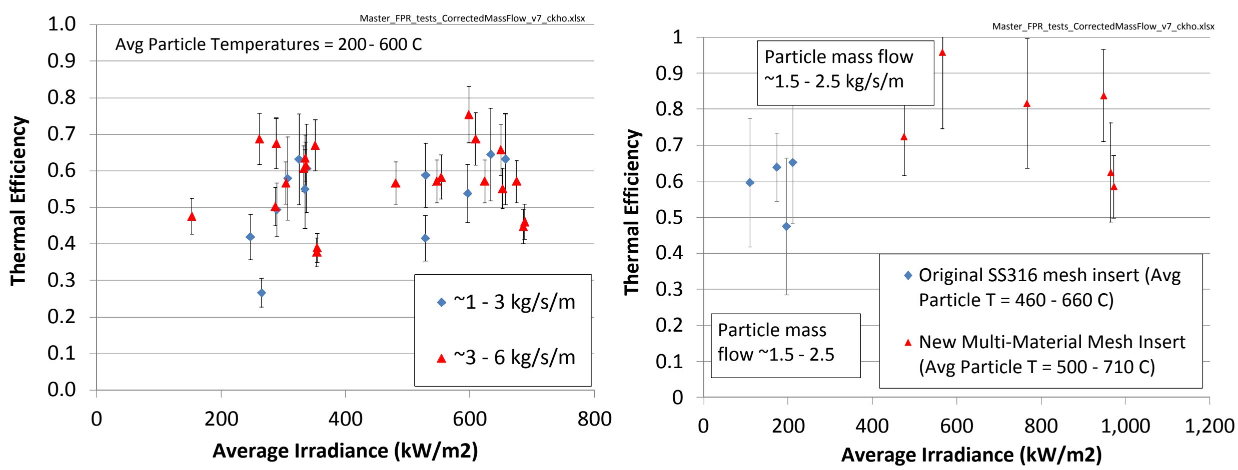

Figure 5. Measured thermal efficiency for free-fall (left) and obstructed-flow (right) receiver tests. Error bars represent one standard deviation.

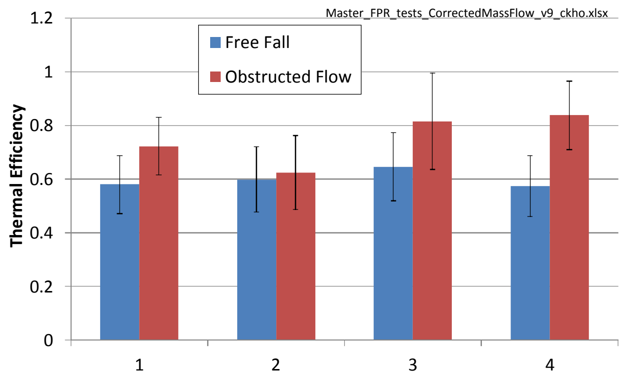

Figure 6. Thermal efficiency comparisons for comparable tests with similar mass flow, irradiance, and inlet temperatures.

PARTICLES

Studies were performed to identify the ideal size and composition of particles that would be efficiently heated (highly absorptive in the solar spectrum), durable, and affordable. A number of commercially available ceramic particles composed of alumina, silica, and other oxides were tested to evaluate their optical properties and durability. These particles are abundantly available and are used commercially as proppants in the oil and gas industry for hydraulic fracturing. Spherical sintered-bauxite particles were found to be the best candidate material for our application because of its high solar absorptance [22] (>0.9), resistance to abrasion and sintering at high temperatures and pressures [22, 23], and ability to be reduced to rejuvenate its solar absorptance. In addition, 140 formulations were synthesized and tested, and 11 materials maintained >90% solar weighted absorptance after 500 hours of heating in air at 700 °C. The 1 MW_t system deployed at Sandia used CARBO Accucast ID50 particles with a nominal diameter of ~280 μm.

After nearly 200 hours of on-sun testing in the 1 MW_t falling particle receiver prototype, the measured packed-bed solar absorptance of the used particles (0.946 ± 0.003) was found to be statistically the same as that of the unused particles (0.945 ± 0.001) using a two-sample t-test with 95% confidence. Formation of iron oxide (hematite) observed on the particle surface during isothermal testing in ovens may have worn away during testing. Particle loss through attrition and wind was found to be ~0.06% of the average particle mass flow rate. Of the total loss, approximately 38% was due to abrasion (especially from the Olds elevator) and 62% was from loss through the aperture. The average particle diameter of the used particles was found to be ~20% less than that of the unused particles (Figure 7).

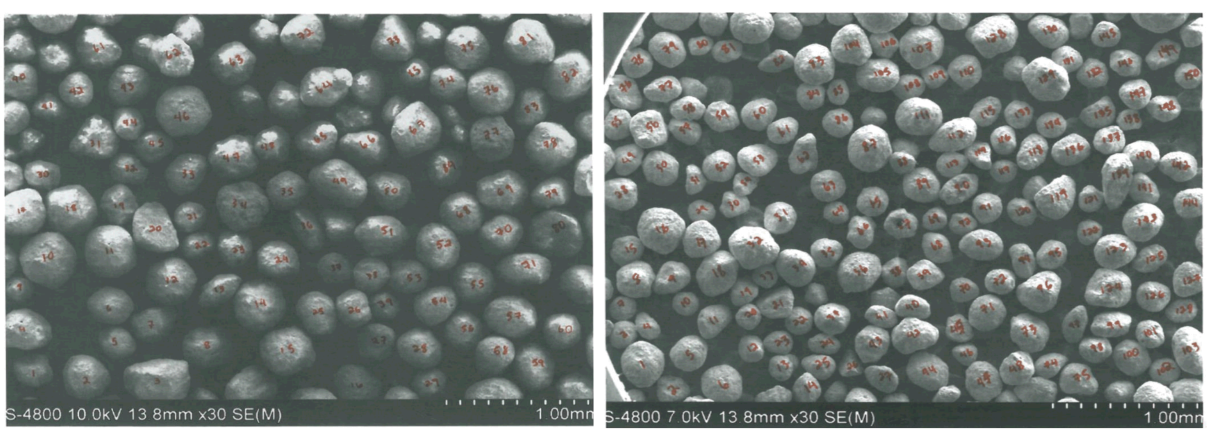

Figure 7. SEM images of ACCUCAST ID50 before (left) and after (right) 187 hours of testing in the on-sun particle receiver prototype. Numbers were added to images for processing particle sizes.

PARTICLE THERMAL STORAGE

The particle collection hopper used in the prototype system consists of a stainless-steel liner with layers of insulation on the outside. For larger-scale systems operating at potentially higher temperature (~1,000°C), studies were performed to evaluate storage systems comprised of insulating firebrick, insulating concrete, and reinforced concrete [24]. This latter design was modeled and tested at a small scale (~300 kW_t), and results showed that the heat loss in these systems was less than 4% per day, which corresponded to ~1% per day for larger-scale systems (~100 MW_t), with costs less than \$15/kW_t. Tests showed no evidence of sintering of the ceramic particles at the expected pressures in a hot storage bin for a large-scale (~100 MW_e) power plant [23, 25].

(a) **(b)**

Figure 8. Ground-based cylindrical particle storage test facility: (a) overall view of the cylindrical bin, (b) the electric heater inserted along the centerline of the storage bin.

PARTICLE HEAT EXCHANGER

Moving packed-bed heat exchangers implementing shell-and-tube and finned shell-and-tube designs were investigated as part of this project to heat a working fluid up to ~700 °C. Tests showed that the particle-side heat transfer coefficient was limiting, but could achieve ~100 W/m^2-K with proper design and spacing of the tubes and fins [26]. Fluidized-bed designs were also characterized from the literature, and higher particle heat transfer coefficients (up to ~600 W/m^2-K) but with higher parasitic power consumption and heat loss associated with the particle fluidization. Follow-on work has been funded by DOE to design and test a particle-to-supercritical-CO_2 heat exchanger integrated with the falling particle receiver system. Fluidized and moving-packed-bed particle heat exchanger designs are being considered

PARTICLE LIFT

The particle lift used in the prototype system is a stainless-steel Olds elevator that can operate at just over 800 °C. A cylindrical casing rotates about a stationary screw to lift particles up ~8 m at a variable controlled rate of up to ~10 kg/s. Because the particles are lifted by friction between the particles and the rotating casing, the lift efficiency is low (~5%). For larger-scale systems, an insulated skip hoist system was designed that can achieve ~80% lift efficiency with a parasitic power consumption less than 1% of the rated electrical output of the CSP plant. The selected Kimberly skip is highly adaptable to this application. As seen in Figure 9, this skip is both filled and discharged from the top and has no complicated and leak-prone bottom hatch. This arrangement facilitates a design that is very simple structurally and mechanically. The single top hatch is opened and closed by motion of the skip, which eliminates any mechanical or hydraulic actuators, and it facilitates a good seal against particle and heat loss during filling and discharge. Any particle spillage will be accumulated in a sump built into the lift shaft, which can be emptied as necessary. The heat loss from the skip is expected to be less than 0.1% of the rated capacity of the system.

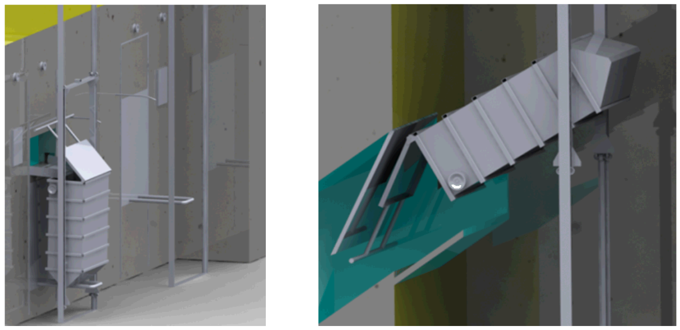

Figure 9. Insulated Kimberly skip charging (left) and discharging (right).

CONCLUSIONS

The ability to achieve average particle outlet temperatures >700°C with an on-sun 1 MW_t falling particle receiver system was successfully demonstrated. Additional testing and challenges that should be addressed in order to scale up to larger systems (e.g., ≥10 MW_e) include the following:

- Integration with a particle-to-working-fluid heat exchanger, potentially operating at high working-fluid temperatures (700°C) and pressures (20 MPa)
- Increasing receiver thermal efficiency through consideration of alternative geometries, sizes, and heat-loss reduction methods
- Reducing particle attrition and loss through higher-efficiency (low-friction) particle lifts and wind protection
- Enabling variable particle mass flow control and measurement to account for varying solar irradiance and cloud conditions. Current test results showed that particle mass flow decreased with increasing temperature due to changes in discharge-plate slot aperture and/or particle/wall friction coefficients.

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