High-Temperature Falling Particle Receiver

Technology Description

Falling particle receivers for concentrating solar power (CSP) systems enable clean, on-demand energy production using concentrated sunlight with highly efficient and inexpensive thermal storage. The falling particle receiver uses sand-like particles that fall through a beam of highly concentrated sunlight focused by an array of mirrors. The particles are heated very efficiently, increasing in temperature by over 100 °C in just a fraction of a second, and are capable of reaching sustainable temperatures over 1,000 °C. Once heated, the hot particles are stored and used to generate electricity in a power cycle or to create process heat.

Pushing the Limits

The world's first continuously recirculating high-temperature falling particle receiver has been tested on-sun at Sandia National Laboratories. Unlike conventional receivers that employ flowing fluids, particle receivers heat particles directly, enabling higher solar concentrations and consequently higher temperatures, higher efficiencies, and lower costs. For example, current conventional solar receivers use molten salt, which decomposes at less than 600 °C, thus limiting the operating temperature and efficiency of the power cycle. Recent on-sun tests with Sandia’s 1 MW falling particle receiver have achieved peak particle temperatures over 900 °C and thermal receiver efficiencies approaching 80% at 1000 suns with particle mass flow rates of 1-7 kg/s. Efficiencies of ~90% are expected for larger-scale (>100 MW).

Comparison of Energy Storage Technologies

<table>
<thead>
<tr>
<th>Energy Storage Technology</th>
<th>Solid Particles</th>
<th>Molten Nitrate Salt</th>
<th>Batteries</th>
<th>Pumped Hydro</th>
<th>Compressed Air</th>
<th>Flywheels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levelized Cost ($/MWh)</td>
<td>10–13</td>
<td>11–17</td>
<td>100–1,000</td>
<td>150–220</td>
<td>120–210</td>
<td>350–400</td>
</tr>
<tr>
<td>Round-trip efficiency (%)</td>
<td>&gt;90%</td>
<td>&gt;90%</td>
<td>&gt;90%</td>
<td>&gt;90%</td>
<td>&gt;90%</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Toxicity/environmental impacts</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Restrictions/limitations</td>
<td>Particle/fluid heat transfer can be challenging</td>
<td>&lt; 600 °C (decomposes above ~600 °C)</td>
<td>Very expensive for large amounts of water required</td>
<td>Only provides seconds to minutes of storage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solar Thermal Receiver Technology</th>
<th>Falling Particle Receiver</th>
<th>Steam Receiver</th>
<th>Molten Salt Receiver</th>
<th>Liquid Sodium Receiver</th>
<th>Volumetric Air Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct energy storage (≥ 6 hours)?</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Maximum irradiance (kW/m²)</td>
<td>Unlimited (≥2,000 kW/m²)</td>
<td>600</td>
<td>600</td>
<td>1,500 - 2,500</td>
<td>900</td>
</tr>
<tr>
<td>Maximum temperature (°C)</td>
<td>650</td>
<td>&gt;600</td>
<td>800</td>
<td>800 – 900</td>
<td>900</td>
</tr>
<tr>
<td>Thermal efficiency (%)</td>
<td>80 – 90%</td>
<td>80 – 90%</td>
<td>90 – 96%</td>
<td>50 – 80%</td>
<td>N/A</td>
</tr>
<tr>
<td>Cost ($/kW)</td>
<td>≥140 – 200</td>
<td>≥140 – 200</td>
<td>≥140 – 200</td>
<td>≥140 – 200</td>
<td>No data</td>
</tr>
<tr>
<td>Restrictions/limitations</td>
<td>High pressure steam requires thicker tubing and more expensive materials</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Contributors:
- Clifford Ho
- Sandia National Laboratories
- Georgia Institute of Technology
- Bucknell University
- King Saud University
- German Aerospace Center (DLR)

Contact:
- Clifford Ho
- Sandia National Laboratories
- (505) 844-2384
- ckho@sandia.gov
- www.sandia.gov/csp

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Particle Receiver*

The 1 MW, falling particle receiver prototype fielded at Sandia National Laboratories includes a particle elevator, cavity receiver, and top and bottom hoppers. The cavity receiver can accommodate either a free-falling curtain of particles or a staggered array of porous chevron-shaped mesh structures that slow the particle flow through the concentrated solar flux for increased temperatures and efficiency. A water-cooled flux target next to the receiver aperture is used to characterize the irradiance from the heliostat field. Nearly 200 hours of on-sun testing have been completed.

- ~300 – 1000 kW/m²
- ~1 – 7 kg/s per meter of particle curtain width
- >700 °C average particle outlet temperature
- >900 °C peak particle outlet temperature
- ΔT = 25 – 200 °C/m (free-fall)
- ΔT = 50 – 300 °C/m (obstructed flow)
- ~80% thermal efficiency

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. Studies were also performed to evaluate storage systems comprised of insulating firebrick, insulating concrete, and reinforced concrete for use in larger-scale systems operating at potentially higher temperatures (~1,000°C). The reinforced concrete design was modeled and tested at a small scale, 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, with costs less than $15/kWt.

Particles

Spherical sintered-bauxite particles were found to be the best candidate material because of their high solar absorptance (>0.9) and resistance to abrasion and sintering at high temperatures and pressures. These particles are commercially available (used as proppants for hydraulic fracturing in oil and gas industry) and inexpensive (~$1/kg for bulk pricing).

Particle Heat Exchanger

Moving-packed-bed heat exchanger designs were investigated 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/m²-K with proper design and spacing of the tubes and fins. Fluidized-beds designs were also characterized from the literature, which yielded higher particle heat transfer coefficients (up to ~600 W/m²-K) but with higher parasitic power consumption and heat loss associated with particle fluidization. Sandia is currently working with industry (Babcock & Wilcox, Solex Thermal Science, and Vacuum Process Engineering) to design and construct a particle-to-sCO2 heat exchanger operating at >700 °C and 20 MPa that can be integrated with our on-sun particle receiver system. Fluidized-bed and moving-packed-bed 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 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.

*Patents and Patents Pending. This technology may be available for licensing. For more information, please contact ip@sandia.gov.