Solar Tower Systems based on Particle Technology

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Solar Tower Systems with Particles: Why?

- Target: higher system efficiency
  - Increased power cycle efficiency by increased process temperatures
    - Steam cycles with up to 620°C: $\eta_{\text{cycle}}$ up to 48%
    - Supercritical CO$_2$ cycles with up to 700°C: $\eta_{\text{cycle}} > 50\%$?
  - Higher cycle efficiency $\Rightarrow$ less heliostats required $\Rightarrow$ lower cost

- Higher cycle efficiency $\Rightarrow$ higher receiver temperature: $T_{\text{rec}} > 600°C$
  - Suitable heat transfer media:
    - New molten salt mixtures: cost, corrosion, degradation?
    - s-CO$_2$?
    - Liquid metals: cost, corrosion, safety?
    - Particles?
Advantages of Solar Particle Systems

Example: bauxite particles

• Very high operation temperature possible (up to 1000°C)
• Direct absorption of solar radiation: high efficiency, high solar flux densities  
  ⇒ no solar flux density limit expected  
  ⇒ reduced need for high temperature materials
• Direct storage of the heat transfer medium
• Direct contact heat exchange with air possible  
  ⇒ low cost heat exchanger in process heat applications
• High temperature spread in storage  
  ⇒ low storage mass, low storage cost
• Chemically stable, no corrosion issues
• Low parasitic power  
  • no freezing ⇒ no trace-heating  
  • low power requirement for transport, receiver operation and heat exchange
• Little safety requirements
• Mass production (“proppants” for fracking)
Materials for Solar Particle Systems

- Sand
- Bauxite particles
- Other natural materials
- Silicon Carbide
- Carbon

- Selection depends on
  - Temperature range
  - Type of receiver
  - Availability of natural materials
  - Application
  - Cost

Example: bauxite, Carbo Accucast ID50
- 75% Al₂O₃, 11% SiO₂, 9% Fe₂O₃, 3% TiO₂
- Packed bed bulk density: ~ 2000 kg/m³
- Packed bed solar absorptivity: 0.91
- Packed bed emissivity: 0.75 @700°C
Principle of a Solar Particle System

- Particles used as
  - Absorber (direct absorption receiver)
  - Heat transfer medium
  - Storage medium
- Receiver temperatures can be freely selected ⇒ techno-economic optimization
- Hot and “cold” storage
- Particle steam generator
- High efficiency cycle
  - steam
    - sub-critical
    - super-critical
  - s-CO₂

Other applications:
- Solar chemistry
- Process heat
- Thermochemical storage
Solar Particle Receiver Classification

- Direct absorption
  - Falling film
    - Free-falling film
    - Obstructed film
  - Rotating receiver
    - Centrifugal
    - Rotary kiln
  - Fluidized bed
  - Entrained
- Indirect absorption
  - Fluidized bed
  - Entrained

Heat transfer medium:
- Particles
- Air heating
Direct Absorption Receiver: Free-falling Film

- Simple concept
- Cheap receiver

Restrictions of free-falling particle film:
- Small range of particle mass flow per film width acceptable
  - mass flow too small: particle film not dense, insufficient absorption
  - mass flow too high: particle film too dense, only front side heated
- Particle velocity can’t be controlled
Direct Absorption Receiver: Free-falling Film

Test setup at SNL
- power \( \sim 1 \text{ MW}_{th} \)

Particle film width \( \sim 1 \text{m} \)
Direct Absorption Receiver: Free-falling Film

- Solar tests at temperatures > 700°C
- Particles: sintered bauxite ("proppants")
Direct Absorption Receiver: Free-falling Film

Results:
- Limited temperature rise per particle drop (< 200°C, depends on load)
- Higher temperatures ⇒ recirculation of preheated particles
- Particle temperatures up to 600°C (steady-state)
- At high mass flow: particle film too thick?
Direct Absorption Receiver: Free-falling Film
Face-Down Cylindrical Receiver

CFD simulation
- 2-phase flow of particles and air
- solar radiation from ray-tracing in volume and on surfaces
Direct Absorption Receiver: Free-falling Film
Face-Down Cylindrical Receiver

Simulation results:
• Design point:
  • 350MW solar in, 300ºC → 800ºC
• Thermal efficiency:
  • ~ 83% without recirculation
  • ~ 92% with 3x recirculation
Direct Absorption Receiver, Obstructed Film

- SNL receiver with insert
- Particles flowing through and over chevron-shaped porous wire meshes
- Reduced particle velocity, relatively constant over film height
- Wire mesh material in prototype: stainless steel
Direct Absorption Receiver, Obstructed Film

- Solar tests at average particle temperatures of 440°C to > 700°C
- Inhomogeneous mass flow distribution over film width (deformed inlet slot)

Overheating $\Rightarrow$ destruction of chevron structures
Direct Absorption Receiver: Centrifugal Receiver

- Rotating receiver
- Centrifugal force keeps particles at the wall
- Residence time controlled by rotational speed
Direct Absorption Receiver: Centrifugal Receiver
10kW Prototype in Laboratory Scale
Direct Absorption Receiver: Centrifugal Receiver
10kW Prototype: Test Results

- Measured wall temperatures indicate homogeneously distributed particle film
- Increasing temperature from receiver inlet (z/L = 1) to outlet (z/L = 0) demonstrates gradual heating of particles
- Particle outlet temperature of about $900^\circ$C reached
Direct Absorption Receiver: Centrifugal Receiver
10kW Prototype: Simulation Results

- Receiver efficiency > 85% predicted at 900°C particle outlet temperature for input heat flux of 1 MW/m²
- Largest heat loss due to radiation
- Convection losses very low (no wind considered)
- Conduction losses according to measurements, high due to prototype scale & design, for real applications, losses of < 1% are possible
Direct Absorption Receiver: Centrifugal Receiver 500kW Prototype

- Receiver with 1 m² aperture is manufactured
- Currently hot commissioning with 100 kW electric heating system (June 16)
- Target particle outlet temperature: 900°C
- 500 kWth receiver tests on the solar tower Jülich planned for spring 2017
- Up to 2.5 MWth and efficiency > 90 % with a commercial field expected
Direct Absorption Receiver: Rotary Kiln

- Mixed absorption:
  - direct: on particles
  - indirect: on walls
- Controlled particle residence time
- Temperatures up to 1000°C demonstrated
- Vertical aperture orientation ⇒ higher solar and convective losses
Direct Absorption Receiver: Other Concepts

Fluidized Bed

- For air heating
- Good heat transfer particle ↔ air
- Tested to above 600°C

Moving Bed

- For reactive particles
- With heat recuperation
Direct Absorption Receiver: Entrained Particles

- Conceptual design
- Carbon particles, 200nm
- Oxidized after absorption
- High efficiency at high temperatures
Indirect Absorption Receiver: Gravity-Driven

- Inner side of tubes irradiated
- Particle flow around tube outside
- Only lab-scale non-solar tests
Indirect Absorption Receiver: Fluidized Particles in Tubes

- Improved heat transfer in tubes
- Tests with single tube up to 750°C
- Tests with tube array up to 585°C
Material Issues

- Solar absorptivity
  - Several options identified to improve solar absorptivity

![Averaged Absorptance Graph](image)

- Attrition / abrasion
  - Centrifugal receiver: direct cost through particle/particle attrition: < 0.00032 €/kWh_th
  - Abrasion on metallic surfaces: further evaluation required
Particle Heat Exchanger Technology
Moving Bed Heat Exchanger (MBHE)

- Indirect heat exchanger for free-flowing (densely packed) bulk materials
- Particles move downwards by gravity, passing along heat exchanging surfaces
- Heat is transferred to medium in the tubes

Advantages of MBHE:
+ Low parasitic loads
+ Good part load behaviour
+ Compact design
+ Low investment and maintenance costs
Particle Heat Exchanger Technology
Fluidized Bed Heat Exchanger

- Good heat transfer characteristics
- Parasitics for fluidization
  - strong influence of particle size
  - small particles preferred
- Multiple stages required

### Table

<table>
<thead>
<tr>
<th>Particle size</th>
<th>( Q_{\text{evp}} )</th>
<th>( Q_{\text{lhf}} )</th>
<th>( P_{\text{blower}} )</th>
<th>( Q_{\text{exhaust}} )</th>
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<tbody>
<tr>
<td>( 100 \cdot 10^{-6} \text{ m} )</td>
<td>117.874 MW(_{th})</td>
<td>117.859 MW(_{th})</td>
<td>4.7 kW(_{el})</td>
<td>18.2 kW(_{th})</td>
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<td>Evaporator</td>
<td>63.539 MW(_{th})</td>
<td>63.493 MW(_{th})</td>
<td>4.8 kW(_{el})</td>
<td>15.4 kW(_{th})</td>
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<td>Superheater</td>
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<tr>
<td>( 250 \cdot 10^{-6} \text{ m} )</td>
<td>110.008 MW(_{th})</td>
<td>109.990 MW(_{th})</td>
<td>27.7 kW(_{el})</td>
<td>121.5 kW(_{th})</td>
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<td>Evaporator</td>
<td>59.281 MW(_{th})</td>
<td>59.211 MW(_{th})</td>
<td>29.0 kW(_{el})</td>
<td>117.8 kW(_{th})</td>
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<td>( 500 \cdot 10^{-6} \text{ m} )</td>
<td>102.258 MW(_{th})</td>
<td>102.232 MW(_{th})</td>
<td>104.1 kW(_{el})</td>
<td>439.1 kW(_{th})</td>
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<td>Evaporator</td>
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<td>110.4 kW(_{el})</td>
<td>464.5 kW(_{th})</td>
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<td>Superheater</td>
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</table>

*) Design point
Economics of Solar Particle Systems

Estimation of relative performance and cost
- Reference system: molten salt, 565°C
- Heliostat field size unchanged
- Significant increase in annual energy yield
- Small reduction of investment cost

<table>
<thead>
<tr>
<th></th>
<th>high efficiency steam cycle</th>
<th>supercritical CO2 cycle</th>
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<tbody>
<tr>
<td></td>
<td>Delta efficiency</td>
<td>Delta item cost</td>
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<tr>
<td>power block</td>
<td>6%</td>
<td>5%</td>
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<tr>
<td>particle receiver</td>
<td>0%</td>
<td>-30%</td>
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<tr>
<td>steam generator</td>
<td>0%</td>
<td>20%</td>
</tr>
<tr>
<td>storage</td>
<td>0%</td>
<td>-30%</td>
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<tr>
<td>heliostat field</td>
<td>2%</td>
<td>0%</td>
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<tr>
<td>total system</td>
<td>8%</td>
<td>100%</td>
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<tr>
<td>LCOE change</td>
<td>-11%</td>
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</table>
Solar Particle Systems: Other Application Options

- Process heat
  - for temperatures up to 1000°C
  - high energy consumption worldwide
  - attractive economics
  - e.g. replacing electricity in metallurgy

- Thermochemical storage
  - use of reactive particles (e.g. $\text{Mn}_x\text{O}_y$)
  - reduction of storage mass and dimension

- Thermochemical cycles for $\text{H}_2$ production
  - use of reactive particles (e.g. redox materials)
Summary

Solar tower systems with particles: promising option

They offer

- High application flexibility
  - Power production
  - Process heat
- Large temperature range
- No freezing, no overheating
- Various receiver technologies
- Systems up to 1MWth tested
- Potential for
  - Increased performance
  - Reduced cost
  - Lower LCoE

but:

- low level of maturity
- significant R&D required
Questions?

Contact: reiner.buck@dlr.de
References:

- DLR R&D results
- B. Gobereit et. al., Assessment of a falling solid particle receiver with numerical simulation, Solar Energy 115 (2015), 505–517