Receivers for Solar Tower Systems

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CSP Characteristics

Solar tower systems:

⇒ higher concentration
⇒ higher process temperature
⇒ higher solar-to-electric efficiency
⇒ reduced collector area
⇒ lower cost
Introduction: Solar Tower Technology

Solar Tower Technology:
• ascending renewable power technology
• high conversion efficiency
• added value:
  • high capacity factor (storage)
  • firm capacity
• significant cost reductions expected
  • technological development
  • improved manufacturing
  • increased maturity (financing)
• high local content achievable
• also suitable for HT process heat
Receiver Classification

Classification by Heat Transfer Medium:
- molten salt
- water/steam
- Air open/closed
- liquid metals
- solid particles
- other gases

Classification by maturity

State of the art technology:
- molten salt
- water/steam

First of its kind technology
- Open volumetric air receiver

Technology in pilot phase
- Pressurized Air Receivers

Technology under development:
- liquid metals
- solid particles
Combination of Receiver and Storage

Receiver/Heat Transfer Medium is relevant for selection of storage system

Storage type:
- sensible
- latent
- (thermochemical)

Storage concepts:
- direct: receiver HTM is also used as storage medium
  - molten salt, particles, (water)
- indirect: a different storage medium is used
  - air/gases, liquid metals
State of the Art: Molten Salt Receivers

- „solar salt“: 60% NaNO3 / 40% KNO3
- **low salt cost** allow use as heat transfer and storage medium
- salt temperatures **up to 565°C** for superheated steam generation
- **good heat transfer** characteristics
- critical: salt **freezing below 220°C**
- **heat tracing required**, draining of receiver and other system components during night
- **salt degradation** at temperatures higher than 600°C
- **corrosion** issues on metallic components (depends on salt quality)

<table>
<thead>
<tr>
<th>Storage Medium</th>
<th>Temperature Cold (°C)</th>
<th>Temperature Hot (°C)</th>
<th>Average density (kg/m³)</th>
<th>Average heat conductivity (W/mK)</th>
<th>Average heat capacity (kJ/kgK)</th>
<th>Volume specific heat capacity (kWh/m³)</th>
<th>Media costs per kg (US$/kg)</th>
<th>Media costs per kWhₜ (US$/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid media</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral oil</td>
<td>200</td>
<td>300</td>
<td>770</td>
<td>0.12</td>
<td>2.6</td>
<td>55</td>
<td>0.30</td>
<td>4.2</td>
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<tr>
<td>Synthetic oil</td>
<td>250</td>
<td>350</td>
<td>900</td>
<td>0.11</td>
<td>2.3</td>
<td>57</td>
<td>3.00</td>
<td>43.0</td>
</tr>
<tr>
<td>Silicone oil</td>
<td>300</td>
<td>400</td>
<td>900</td>
<td>0.10</td>
<td>2.1</td>
<td>52</td>
<td>5.00</td>
<td>80.0</td>
</tr>
<tr>
<td>Nitrite salts</td>
<td>260</td>
<td>450</td>
<td>1,825</td>
<td>0.57</td>
<td>1.5</td>
<td>152</td>
<td>1.00</td>
<td>12.0</td>
</tr>
<tr>
<td>Nitrate salts</td>
<td>265</td>
<td>565</td>
<td>1,870</td>
<td>0.52</td>
<td>1.6</td>
<td>250</td>
<td>0.50</td>
<td>3.7</td>
</tr>
<tr>
<td>Carbonate salts</td>
<td>450</td>
<td>850</td>
<td>2,100</td>
<td>2.0</td>
<td>1.8</td>
<td>430</td>
<td>2.40</td>
<td>11.0</td>
</tr>
<tr>
<td>Liquid sodium</td>
<td>270</td>
<td>530</td>
<td>850</td>
<td>71.0</td>
<td>1.3</td>
<td>80</td>
<td>2.00</td>
<td>21.0</td>
</tr>
</tbody>
</table>
Molten Salt Systems
Molten Salt Systems

- **GEMASOLAR:**
  - 20MW el.
  - External tube receiver
  - operation since 2011
  - 290°C – 565°C
  - 120 MW$_{th}$ @DP
  - $\eta_{rec,DP} \approx 88\%$
Molten Salt Systems

- **Crescent Dunes** (SolarReserve)
  - Molten salt
  - $110\text{MW}_{\text{el}}$
  - External tube receiver
  - Receiver outlet temperature: $565^\circ\text{C}$
Strategies improving Molten Salt Systems

- **Higher temperature molten salt:**
  - Higher steam parameters
  - Smaller heat exchanger
  - Smaller storage
  - Less critical operation (over temperature receiver)

- **Higher receiver efficiency** by:
  - Reduction of thermal losses
  - Cavity arrangement
  - Face down (can design)
  - Using standard vacuum absorber for first temperature step
  - Higher absorption of solar radiation ((selective) coatings)

- **Optimization of operation**
  - Real time aim point strategy for homogenous receiver temperature (→ life time!)
  - Solar pre-heating of receiver
  - Faster start-up
  - Avoiding draining of receiver during clouds
State of the Art: Saturated Steam

- **PS10/PS20**
  - direct irradiated absorber tubes (250°C@40Bar)
  - 11/20 MW_{el}
  - cavity receiver
Saturated Steam Systems

**Brightsource:**
- Ivanpah 377MW
- direct Steam (550°C)
- external tube receiver
Strategies improving Superheated Steam

- **Higher steam temperatures** and pressures for higher efficiency at the power block
- **Higher loads for absorber tubes** (pressure and temperature)
- **Three zones in receiver** with different heat transfer coefficients:
  - pre-heating
  - evaporation
  - superheating
First-of-its-Kind: Open Volumetric Air Receivers

Volumetric Receiver Principle

drastic increase of heat transfer surface area
First-of-its-Kind: Open Volumetric Air Receivers

- 0.02 m² Absorber
- 0.57 m² Submodul
- 5.7 m² Solair Receiver (PSA)

22.7 m² Receiver (Jülich)
Power Plant Jülich (DLR)

process parameters:
- pressure: ambient
- return air: 120°C
- receiver air outlet: 680°C

material load parameters:
- max. temp.: 1100°C (front)
- max. load: 1000kW/m²
- temp. gradient: ~100K/cm
- average mass flow: 0.55 kg/m²-s

dynamic operation:
- air outlet temp. of single cup: max. temp. change ≈3.3K/sec
First-of-its-Kind: Open Volumetric Air Receivers Strategies for Improving

**Improve of Absorber**
- Higher Porosity
- Higher heat transfer surface per volume
- Stable mass flow
- Extension of durability

**Improve of System:**
- Less auxiliary energy
  - Decrease of pressure drop
- Online aiming point strategy
- Cavity receiver
  - Increase of air return ratio
- Operator assistance system
Technology in Pilot-Phase: Pressurized Air Receivers

- **pre-heating of the compressed** air of a Brighton cycle
- **currently two power levels** are under development:
  
  **large systems:**
  - 5-150 MW el.
  - combined with steam cycle

  **small systems:**
  - 0.1-5 MW el. (recuperated turbine)
  - combined with cooling/heating (desalination)
Technology in Pilot-Phase: Receiver Development

- air outlet temperature: 800-1000°C
- pressure: 4-16 Bar\textsubscript{abs.}
- pressure drop: 100-400mBar
- materials: high temperature alloy, ceramics, fused silica

tube receivers

volumetric receivers

ceramic plate receiver
Technology in Pilot-Phase: First Pilot (SOLUGAS)

- EU-project under leadership of ABENGOA SOLAR NT
- Test of a 3MW\textsubscript{th} metallic tubular receiver
  - Inlet temperature: 330°C
  - Outlet temperature: 800°C
  - Pressure: 10Bar\textsubscript{abs}
- Since summer 2012: more than 700h of solar operation
- Design values reached and simulation models validated
- Next step: Integration of Volumetric Pressurized receiver (1MW\textsubscript{th} /1000°C)
Technology in Pilot-Phase: Receiver Development
Closed Volumetric Receiver

- **high efficiency** (>80%) caused by…
  - „volumetric“ absorption of radiation
  - relatively low absorber temperatures
  - low thermal reradiating
- **low pressure drop** (< 30mbar)
- high possible outlet temperatures (>1000°C)
- **proven technology**

![Diagram of volumetric receiver](image)
Technology in Pilot-Phase: Receiver Development Tube Receiver and Design methods

- using commercial FEM/CFD codes for the thermal and mechanical layout
- using the raytracing code SPRAY
- thermal field can be used for mechanical simulation (strain, stresses)
- parametric approach allows easy variations (geometry, load cases) and optimization

FE- Model  
Raytracing using
- FE- Model
- Heliostat field data
- Time point

Solar heat fluxes

Temperature distribution

Other thermal boundaries
- Radiation exchange
- Forced convection to fluid
Technology in Pilot-Phase: Receiver Development
Ceramic Plate Receiver

- mass flow is distributed to several parallel absorber tubes by a tubular header
- absorber tubes should have small diameters for best heat transfer.
- the thermal strain of each absorber tube has to be compensated.
- tubular collector collects the heated fluid.
- design of receiver has to fulfil thermodynamic, hydraulic and economic needs.

Different Panel Arrangements
Technology in Pilot-Phase: Receiver Development Ceramic Plate Receiver

Material benefits of SiC ceramic

- **High** thermal conductivity
- Very low thermal expansion coefficient
- Temperature **stability up to 1500°C** (in air)
- Gas-tight
- **High strength**
- “Black without coating”
- Design of inner structure
Technology under development: Liquid Metal Receivers

- Large temperature range
- High heat transfer coefficients

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Salt</td>
<td>600°C</td>
</tr>
<tr>
<td>NaK</td>
<td>785°C</td>
</tr>
<tr>
<td>K</td>
<td>774°C</td>
</tr>
<tr>
<td>Na</td>
<td>890°C</td>
</tr>
<tr>
<td>Pb-Bi</td>
<td>1533°C</td>
</tr>
<tr>
<td>Pb</td>
<td>1744°C</td>
</tr>
<tr>
<td>Sn</td>
<td>2620°C</td>
</tr>
</tbody>
</table>

Heat transfer coefficients:

- Hitec (53%KNO₃ + 40%NaNO₂ + 7%NaNO₃): 4625 W/m²/K
- Solar Salt (60%NaNO₃ + 40%KNO₃): 5015 W/m²/K
Technology under development: Liquid Metal Receivers

First receivers tested in the 80’s with sodium as HTF achieved high efficiencies.

Receiver test in the USA: Sandia CRTF
- 750 litres, 70 hours

Plant test in Spain: PSA
- 70,000 litres, 5 years

After a sodium fire in 1986 in Almeria, investigation of liquid metals in solar power systems was stopped!
## Technology under development: Liquid Metal Receivers

### Ongoing Research

<table>
<thead>
<tr>
<th>Conventional technologies</th>
<th>Innovative technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Steam turbine ($\eta \approx 45%$)</td>
<td>• Thermo-electrical Generator (TEG: Seeback-Effect) ($\eta \approx 5%$)</td>
</tr>
<tr>
<td>• Gas turbine ($\eta \approx 40%$)</td>
<td>• Thermionic Power Generator (Edison-Richard-Effect) ($\eta &lt; 5%$)</td>
</tr>
<tr>
<td>• Gas- and steam turbine ($\eta \approx 55%$)</td>
<td>• <strong>Alkali-Metal Thermal Electric Converter (AMTEC)</strong>, Electrochemical device for direct conversion of heat to electricity ($\eta \approx 15\ldots40%$)</td>
</tr>
<tr>
<td></td>
<td>• <strong>Liquid Metal Magneto-hydrodynamic Generator (LM MHD)</strong>, energy conversion: heat $\rightarrow$ kinetic energy $\rightarrow$ electricity ($\eta \approx 20\ldots60%$)</td>
</tr>
</tbody>
</table>
Technology under development: Liquid Metal Receivers

Conceptual study

![Graph showing efficiency with power output versus temperature for different materials and receiver types.](image-url)
Technology under development: Direct Absorbing Particle Receiver

- **direct absorbing** of solar radiation at **small ceramic particles**
- **ceramic particles as heat transfer** and **storage** medium
- **high temperature capability** (>900°C) for power generation and process heat
- **no limits in flux densities** (no wall between heat absorption and heat transfer medium)
Technology under development: Direct Absorbing Particle Receiver: 1. Approach – Falling Particle Curtain

- **optically dense particle film** near the inner surface of a cylinder/box
- **gravitation forces give falling** speed and duration of particle in solar radiation
- **re-circulating of the particles** necessary to obtain design outlet temperature
- **concentrated solar radiation** through the opening at the bottom
- **high level models developed** (coupling of CFD, raytracing and particle movement)
Technology under development: Direct Absorbing Particle Receiver: 2. Approach – Centrifugal Particle Receiver

- optically dense moving particle film on the inner surface of a rotating cylinder
- gravitation and centrifugal forces → particle retention time can be controlled by rotation speed
- Prototype (10kW) successfully tested up to 900°C
R&D Outlook on Technologies (plus Trough Tech.)

- **State of the art technologies**
  - Trough with thermo oil
  - Tower with steam
  - Tower with salt
  - Fresnel with steam

- **First-of-its-Kind technologies**
  - DSG in trough
  - Open vol. Receiver
  - Industrial process heat

- **Technology in pilot phase**
  - Salt in Trough/Fresnel
  - GT + Tower

- **Technology under development**
  - Particle (Tower)
  - Liquid metal (Tower)
  - Development of new HTF (Tower/Trough/Fresnel)
  - Solar Fuels

**Field of R&D**

- Methods on qualification, operation optimization, degradation, side evaluation
- Optimization of components
- Adaptation of conventional components for solar applications
- Pilot plants and Development
- Prototype testing (lab scale) / Scale-up / Modeling / materials and properties / system evaluation / basic research on effects, kinetics, conversion rates ....
Thank you for your attention!