Porous Materials For High-Temperature Solar Absorbers

Sandro Gianella
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“Using only 0.1% of the earth’s land space with solar collectors that operate with a collection efficiency of merely 20%, one could gather more than enough energy to supply the current yearly energy needs of all inhabitants of the planet (≈1.2 x 10^{14} kWh).”

CSP Technologies
CSP Technologies

Parabolic through

Line focussing systems

Linear Fresnel
CSP Technologies

Point focussing systems

Dish

Solar tower

International Symposium on High Temperature Solar Materials, Yeungnam University
## CSP Technologies

### Comparison

<table>
<thead>
<tr>
<th></th>
<th>Parabolic Trough</th>
<th>Solar Tower</th>
<th>Linear Fresnel</th>
<th>Dish-Stirling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Typical capacity (ME)</strong></td>
<td>10-300</td>
<td>10-200</td>
<td>10-200</td>
<td>0.01-0.025</td>
</tr>
<tr>
<td><strong>Maturity of technology</strong></td>
<td>Commercially proven</td>
<td>Pilot commercial plants</td>
<td>Pilot projects</td>
<td>Demonstration projects</td>
</tr>
<tr>
<td><strong>Operating temperature (°C)</strong></td>
<td>350-550</td>
<td>250-565</td>
<td>390</td>
<td>550-750</td>
</tr>
<tr>
<td><strong>Plant peak efficiency (%)</strong></td>
<td>14-20</td>
<td>23-35</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td><strong>Annual solar-to-electricity efficiency (net, %)</strong></td>
<td>11-16</td>
<td>7-20</td>
<td>13</td>
<td>12-25</td>
</tr>
<tr>
<td><strong>Collector concentration</strong></td>
<td>70-80 suns</td>
<td>&gt; 1000 suns</td>
<td>&gt; 60 suns</td>
<td>&gt; 1300 suns</td>
</tr>
<tr>
<td><strong>Receiver/Absorber</strong></td>
<td>Absorbers attached to collectors</td>
<td>External surface or cavity receiver</td>
<td>Fixed absorber</td>
<td>Absorber attached to collector</td>
</tr>
</tbody>
</table>

**Source:** IRENA Report, Concentrating Solar Power, Volume 1, Issue 2/5, June 2012
CSP Technologies

Electricity production

Puerto Errado 2, Fresnel CSP Power Station
30 MW, Novatec Solar

Parabolic-trough power plant, California's Mojave Desert.

Maricopa Dish Stirling Plant, Peoria, Arizona, 1.5 MW

PS10 and PS 20 solar towers, Sevilla, Spain
CSP Technologies

Energy carriers production

SOLHYCARB reactor, Methane splitting, ETH Zürich

ZnO reactor, Water splitting, ETH Zürich

Component tests for SOLHYCARB, PSI

100-kW scale up reactor, ETH Zürich
CSP Technologies

Scope

Process Heat

Lavoisier solar furnace, Paris 1772

Solar furnace of Odeillo, Pyrénées-Orientales, France

Solar Process Heat (SO-PRO)
CSP Technologies

Global market trends

Facts

- Activity re-started after more than 15 years
- By the end of March 2012: 1.9 GW installed CSP capacity
- Leading markets: USA and Spain (90% of current installed CSP capacity)

- Currently dozens of CSP plants in construction
- 20 GW under development worldwide

- Capacity distribution:
  - 1.8 GW parabolic through (94%)
  - 70 MW solar tower
  - 31 MW Fresnel reflector

CSP Technologies

Global market trends

Source: European Solar Thermal Electricity Association (ESTELA), The First Five Years Of ESTELA Report, 2011
High Temperature Absorbers
High Temperature Absorbers

Solar tower, molten salt

Parabolic Dish, stirling engine
High Temperature Absorbers

Typology

Tube receiver and volumetric receiver concept.

High Temperature Absorbers

Solar tower tube receiver

- Metallic tubes (special alloy)
- Steam or molten salt carrier
- Max. 650°C (flow temperature)
- Tube outside temperature < 900°C
- Corrosion and deterioration
- Special coatings

Solar Two in Daggett, California, 10-MW solar thermal electric power plant
**High Temperature Absorbers**

**Parabolic dish tube receiver**

- SES SunCatcher solar receiver
- Eurodish receiver material, Solo Stirling GmbH
- Metallic tube receiver for parabolic dish.
High Temperature Absorbers

Solar tower volumetric receiver

Open volumetric receiver HiTRec, DLR

Implementation, KAM, Jülich

Closed (pressurized) volumetric receiver REFOS, DLR and CIEMAT, Spain

Implementation, Plataforma Solar de Almeria, Spain
HiTRec receiver, DLR

Stobbe SiSiC receivers

Open volumetric receiver material

- Si-SiC honeycomb
- Up to 1000°C air temperature achieved
- 80% efficiency from solar to air
High Temperature Absorbers

Open volumetric receiver material

- Diesel particulate filter technology
- Mass product
- Relatively cheap

First commercial open volumetric absorber material, St. Gobain
Closed volumetric receiver material

Decomposition diagram of REFOS receiver

SiC foam as radiation absorber material
High Temperature Absorbers

Parabolic dish closed volumetric receiver material

- The Porcupine receiver, developed by Karni et al. at Weizmann Institute, Israel
- Cross flow
- SiC foams as absorber material

Porcupine solar receiver, Weizman, Israel

Parabolic dish receiver by HelioFocus, Israel

Porcupine implementation by HelioFocus, Israel
High Temperature Absorbers

Absorber material importance

- First transformation point, radiation to heat
- Higher absorption + higher transmission to flow → lower LCOE
- Very low cost contribution, big effect

“One of the most promising developments for towers relies on the development of receivers that can operate with alternative fluids which can lead to higher operating temperatures.”

Source: ATKearney, ESTELA, Solar Thermal Electricity 2025, June 2010

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Absorber Optimization
Absorber Optimization

Working conditions

- Resistance up to 1200°C (air)
- Support radiation flux densities >1,000 kW/m²
- Thermal shock resistance (>200 °C/min)
- Thermal cycle resistance
- High thermal conductivity
- High absorptivity
- High surface area
- Low pressure drop
- Low cost
- Long life span

Solar Power Plant, Sevilla, Spain
Absorber Optimization

- Physical, thermal and mechanical properties
- Architecture
- Life span
- Cost

Potential absorber materials
Absorber Optimization

Material properties

### Density [g/cc]

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [g/cc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiSiC</td>
<td>3.1</td>
</tr>
<tr>
<td>Alumina</td>
<td>3.96</td>
</tr>
<tr>
<td>Yttria Stab. Zirconia</td>
<td>6.02</td>
</tr>
<tr>
<td>Nickel Superalloy</td>
<td>8.89</td>
</tr>
</tbody>
</table>

### Modulus of elasticity [GPa]

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of Elasticity [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiSiC</td>
<td>410</td>
</tr>
<tr>
<td>Alumina</td>
<td>370</td>
</tr>
<tr>
<td>Yttria Stab. Zirconia</td>
<td>210</td>
</tr>
<tr>
<td>Nickel Superalloy</td>
<td>205</td>
</tr>
</tbody>
</table>

### CTE linear at 25°C [μm/m-°C]

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE linear at 25°C [μm/m-°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiSiC</td>
<td>4.3</td>
</tr>
<tr>
<td>Alumina</td>
<td>5.5</td>
</tr>
<tr>
<td>Yttria Stab. Zirconia</td>
<td>10.3</td>
</tr>
</tbody>
</table>

### Thermal conductivity [W/m-K]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity [W/m-K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiSiC</td>
<td>160</td>
</tr>
<tr>
<td>Alumina</td>
<td>46</td>
</tr>
<tr>
<td>Yttria Stab. Zirconia</td>
<td>2.2</td>
</tr>
<tr>
<td>Nickel Superalloy</td>
<td>9.8</td>
</tr>
</tbody>
</table>
Absorber Optimization

SEM-images of different Si-SiC microstructures

- Two different sizes of particles homogeneously distributed in fused Silicon
- Microporosity: ~0%
- Passive oxidation layer
- Low crack formation
Absorber Optimization

Material architecture

Honeycombs:
- 2-Dimensional flow
- Hot spots
- Mass product

Foams:
- 3-Dimensional flow
- Better temperature distribution
- Not yet a mass product
Absorber Optimization

Honeycombs

Comparison of measured and 2-D interpolation thermal maps in °C of HiTRec-II

Failure of absorber module

Absorber Optimization

Material architecture

Foams

IR-Camera analysis of ErbiSiC foams at DLR, Germany

Solar simulation lamps, DLR, Germany
Absorber Optimization

Material architecture

Other architectures

Reticulated Foam (ErbiSiC R)  Filamentous structure (ErbiSiC F)  Custom-designed structure
Absorber Optimization

Custom designed architectures

- Simulate phenomena and operation
- Design best structure
- Produce template with rapid prototyping
- Ceramize

Get best suited architecture

Custom-designed structure produced by Erbicol SA
Life span
Applications of Si-SiC open-cell materials

- Porous burner
- Catalyst support
- Reforming
- Structural materials
- High-temperature heat exchanger
- Static mixer
Life Span

**Situation**

- No accelerated life time test is possible
- Barrier between active and passive oxidation (1400°C)
- Real application conditions are needed

**Difficulties**

**Analysis and prediction**

- Main phenomena that influence the life time of foams:
  - Oxidation
  - Crack formation
- Investigate cycled ceramics using:
  - Mechanical analysis: flexural strength and/or compression
  - Mass difference
  - Microanalysis
  - Tomography
  - SEM and SEM-EDS
  - XRD
Mass evolution

Mass gain  ➔ passive oxidation

Mass loss  ➔ active oxidation and spalling

Passive oxidation layer

As produced  ➔ After 100h  ➔ After 1000h

Life Span

- Decrease in first hours
- Almost constant thereafter

Number of cracks

- First three ON/OFF cycles
- Crack formation decreases drastically

Life Span

Long time behaviour

- Silica layer formation
- Maximal crack formation during first operation hours
- Mechanical strength decreases 30% during the very first hours of operation

Look at first hours

International Symposium on High Temperature Solar Materials, Yeungnam University
Summary
Summary

- Increase and differentiation of CSP market increases size for solar absorbers
- Absorber material performance is key to LCOE decrease
- Key features of absorbers: high temperature, high absorption, high thermal conductivity, low cost, long life span
- Ceramic open cell materials have potential as solar absorber
- Custom designed structures probably will allow best performance
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