High-performance Stellio heliostat for high temperature application

Thomas Keck, sbp sonne gmbh
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1. Introduction

Motivation for high performance heliostats

High temperature processes mean:
→ High surface temperatures of receivers/absorbers
→ Increased thermal losses (IR radiation goes with $T^4$)

System design requirements:
• Cavity receivers!
• Apertures: as small as possible
• Heliostats: high optical quality (small beam diameter), low tracking errors
next-CSP (1)

EU funded project:
- Fluidized particle-in-tube receiver for 750 °C
- Particles used as thermal storage
- 3 MW$_{th}$ prototype receiver (Whittaker Engineering) at Themis plant in Odeillo/France, to be completed in 2020, operated by CNRS
next-CSP (2)

Further presentations and posters on next-CSP:

• A. Le Gal et al., "MW-scale prototype of the fluidized particle-in-tube solar receiver. Design, control and first experiments at Themis tower.", presentation given in WED-1A, 11:10

• B. Grange et al., "Simulation of the Next-CSP solar loop including a hybrid gas turbine", presentation given in WED-2D, 15:50

• B. Grange et al., "Comparison of simulated and measured flux distributions at the aperture of the Next-CSP solar receiver", presentation given in WED-1C, 11:10

• F. Siros et al., "Next-CSP Concept with Particle Receiver Applied to a 150 MWe Solar Tower", presentation given in FRI-1C, 10:50


• K. Whittaker, Keith Watt, "Manufacturing of the Main Components of the Next-CSP Project Solar Pilot Plant", poster session Advanced Materials Mon 16:00
Stellio heliostat

Stellio: developed for large plants, commercially available
Selected for Hami Solar Tower/China (under construction)

Main characteristics:
- Net reflective surface: 48.5 m²
- Novel kinematics with inclined axes (slope drive)
- Two linear actuators
- Reflector substructure with high stiffness
- High optical quality

www.stellio.solar
2. Heliostat quality parameters

- **Slope error:**
  \[ \sigma_{\text{beam}} = 2 \times \sigma_{\text{slope}} \]
  \[ \sigma_{\text{slope,2D}} = \sqrt{\sigma_{\text{slope,x}}^2 + \sigma_{\text{slope,y}}^2} \]
  \[ \rightarrow \text{Stellio: } \sigma_{\text{slope,2D}} (\text{SD}_{\text{tot}}) = 1.5 \text{ mrad} \]

- **Tracking error:**
  \[ \sigma_{\text{pointing}} = 2 \times \sigma_{\text{tracking}} \]
  \[ \sigma_{\text{tracking,2D}} = \sqrt{\sigma_{\text{tracking,x}}^2 + \sigma_{\text{tracking,y}}^2} \]
  \[ \rightarrow \text{Stellio: } \sigma_{\text{tracking,1D}} = 0.6 \text{ mrad} \]
### 3. Optical quality improvements

#### Potential improvements

<table>
<thead>
<tr>
<th>Measures</th>
<th>Potential</th>
<th>Engineering effort</th>
<th>Cost increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase of purlin stiffness</td>
<td>++</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>Increase of cantilever arm stiffness</td>
<td>+</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>Increase number of mirror supporting points</td>
<td>+++</td>
<td>high</td>
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</tr>
<tr>
<td>Modification of supporting point details</td>
<td>+</td>
<td>medium</td>
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<td>Increase facet stiffness</td>
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Identify improvement measures for optical quality

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Standard Stellio slope errors

Example of slope errors from Hami field: heliostat #6813, Aug. 2020

$SD_{\text{tot}} = 1.27 \text{ mrad}$
Optical quality improvements

Standard Stellio mirror supporting

Facet with 5 purlins and 13 supports

Stellio mirror support structure
Mirror deformations under deadweight

Facet with 5 purlins and 13 supports

Facet with 6 purlins and 17 supports

$\sigma_{\text{slope,2D}} = 1.5$ mrad

$\sigma_{\text{slope,2D}} = 1.3$ mrad

Optical quality improvements
Cost impact

Extra cost for additional purlins and mirror supports, incl. assembly:

Approx. 2 % of heliostat cost (wo. foundations)
4. Tracking quality improvements

## Potential improvements

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<td>Increase limit switch precision</td>
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<tr>
<td>Improve actuator corrections by control</td>
<td>+</td>
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<td>zero</td>
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<td>(temperature, normal force, pitch)</td>
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<td>Increase pylon head stiffness</td>
<td>+++</td>
<td>medium</td>
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<tr>
<td>Refinement of heliostat calibration</td>
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Identify improvement measures for tracking quality

Potential improvements

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Linear actuators (1)

ACME spindle and nut
- Trapeze groove, plastic nut
- Sliding contact
- Low efficiency

Ball screw spindle and nut
- Circular groove, nut with steel balls
- Rolling contact
- High efficiency

Tracking quality improvements

www.barnesballscrew.com
**Linear actuators (2)**

**ACME spindle and nut**
- Backlash temperature dependent, subject to wear
  → **1.0 mm avg.** over service life*
- Medium stiffness, considerable loss in plastic nut

**Ball screw spindle and nut**
- Backlash almost constant, little wear
  → **0.3 mm avg.** over service life*
- High stiffness, all parts from metal
  → **2-3 fold** of ACME

* incl. trunnion and rod end bearing play

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Tracking quality improvements
Increased stiffness of pylon head

- Modified geometry + optimized material thickness → increased stiffness
- Mass remains constant
Improved calibration

1. Beam Characterization System (BCS):
   Target/camera based → novel calibration solutions, e.g. drone based

   Advantages:
   - independent of sun, clouds and target availability
   - potentially better accuracy
   - high calibration frequency.

   → System developed together with CSP Services and others in HelioPoint project
   (W. Jessen et al.: A Two-Stage Method for Measuring the Heliostat Offset,
   Poster session Measurement Systems, Wed 18:45)

2. Algorithm for tracking error corrections:
   Potential for improvement, can’t yet be quantified

   → Estimated uncertainty of measured beam pointing reduced by half
Combined tracking error

Total tracking error is combined from:
- backlash
- drive stiffness
- pylon/foundation/structure stiffness
- calibration/tracking algorithm accuracy

Dead weight induced errors are compensated to a good part but wind effects remain.

All errors are overlaid by RMS.

→ Reduction from 0.6 to 0.4 mrad is expected (1D)
Cost impact

- Ball screw actuator cost: approx. 30-40 % higher than ACME
- Pylon head improvement cost: ±0
- Precise calibration cost: ±0

→ approx. 5 % increase of heliostat cost (wo. foundations)
5. Techno-economic analysis

LCoE analysis by EdF

- Simple model, O & M cost neglected since these are same for all options
- Discount rate: 4 %, lifespan: 25 years
- Sample power plant assumed, using next-CSP technology:
  - Peaker plant, 150 MW_{el}
  - CSP full load: 5 hrs
  - Daily thermal / electric energy: 1.6 GWh / 0.75 GWh
- Specific LCoE changes:
  +1 M€ in CAPEX results in LCoE change of +0.28 €/MWh_{el}
  +1 MW_{el} in net output results in LCoE change of -0.63 €/MWh_{el}
LCoE analysis results

Reference system

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Receiver outlet power</td>
<td>343 MW\textsubscript{th}</td>
</tr>
<tr>
<td>Plant net electric power</td>
<td>150 MW\textsubscript{el}</td>
</tr>
<tr>
<td>CAPEX</td>
<td>340 M€</td>
</tr>
<tr>
<td>LCoE</td>
<td>95 €/MWh\textsubscript{el}</td>
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</tbody>
</table>

High performance Stellio

<table>
<thead>
<tr>
<th>Improvement measures</th>
<th>CAPEX increase (M€)</th>
<th>Performance gain (MW\textsubscript{th})</th>
<th>LCoE change (€/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope error</td>
<td>1.55</td>
<td>4.93</td>
<td>-0.93</td>
</tr>
<tr>
<td>Tracking error</td>
<td>4.16</td>
<td>5.78</td>
<td>-0.44</td>
</tr>
<tr>
<td>Combined</td>
<td>5.71</td>
<td>10.71</td>
<td>-1.37</td>
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Percental

Tracking error improvement

<table>
<thead>
<tr>
<th>Improvement measures</th>
<th>LCoE change (€/MWh\textsubscript{el})</th>
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<tbody>
<tr>
<td>Ball screw actuator</td>
<td>0.02</td>
</tr>
<tr>
<td>Improved pylon head</td>
<td>-0.34</td>
</tr>
<tr>
<td>Improved calibration</td>
<td>-0.33</td>
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Techno-economic analysis
6. Conclusions

- Overall, LCoE reduction of approx. 1.5 %
- Major gain by increased number of mirror supports

Notes:
- Conceptual study, no/little optimization
- Simplified calculations were applied

→ High performance Stellio provides some economic advantage for high temperature processes
Acknowledgements

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 727762, project acronym next-CSP.
Thank you very much for your attention!