Advanced Measurement Systems
to evaluate CSP Plants

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DLR Institute of Solar Research

Knowledge for Tomorrow
Outline

• Challenges for measurements in CSP power plants

• Parabolic Trough Fields:
  • Airborne predictions of optical field performance
  • Hydrogen accumulation in parabolic trough receivers
  • Cloud shadow prediction in the solar field

• Solar Tower
  • Optical quality of heliostat field and flux distribution on receiver
  • Air return ratio in open volumetric receiver systems

• Summary
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Challenges for measurements in CSP power plants

- Measurement object extended or distributed over several square miles
- Limited access (e.g. tower)
- Measurement should not disturb operation
- Sensors preferably non invasive
- High measurement precision requirements
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• Summary
QFly – airborne prediction of the optical performance of parabolic trough collector fields

QFly UAV

Failure Detection, Quality Control, Optimization

High resolution

Survey

Thermo

Mirror shape

HCE position

Mirror shape

Alignment

Torsion

Tracking

Defective HCEs

Heat loss

50 MW PTC solar field (Andasol I)

25%/day

50%/day

5%/day
2. Qualification of Concentrators
Deflectometry
2. Qualification of Concentrators
Deflectometry – Image Acquisition
QFly measurement principle

• Plan for Flight Route using GPS waypoints
• Aerial images showing absorber tube reflex
• Scaling/reference system for close-range photogrammetry
QFly measurement principle

- Calculation of camera positions relative to each collector via photogrammetry
- Artificial, coded and natural markers
- Accuracy of 3D coordinates ~ 5 mm
QFly measurement principle

- Calculation of lateral and vertical HCE deviation from focal line via photogrammetric approach
- Deviations Qfly to reference:
  - RMS dX < 2.0 mm
QFly measurement principle

- Calculation of slope deviations in curvature direction (SDx, in mrad) from absorber reflex, camera positions and absorber position
QFly measurement principle

- Intercept factor via ray-tracing based on measured geometry
- Includes blocking and shading effects
- Assumptions on other error sources
QFly measurement principle

<table>
<thead>
<tr>
<th>Creation of Flight Routes</th>
<th>Data Acquisition</th>
<th>Photogrammetry</th>
<th>HCE positioning</th>
<th>PTC Geometry- &amp; Performance evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waypoints based on Solar Field Parameters</td>
<td>Reference System</td>
<td>Aerial Images</td>
<td>3D setup</td>
<td>HCE_dX, HCE_dZ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SD_X, IC</td>
</tr>
</tbody>
</table>

Effort per collector (SCA) 150 m:

- 2 hours
- 0.5 hours
- 4 hours
Validation

**Optical:**
- Comparison with reference data from photogrammetry
- Mirror:
  - Difference of SDx RMS values < 0.4 mrad (due to limited spatial resolution of photogrammetry)
- Absorber tube position RMS of differences:
  - < 2.0 mm horizontal
  - < 2.1 mm vertical

**Thermal:**
- Comparison with thermal efficiency of EuroTrough module on Kontas test-bench (PSA Almeria)
- Good agreement between $\eta_{opt}$:
  - via thermal measurement
  - via QFly measurement
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Hydrogen accumulation in parabolic trough receivers: Effects and Counteractions

- Hydrogen accumulation would deteriorate vacuum insulation of receivers

- Counteractions against hydrogen in receiver (getter, barrier coating) designed for $H_2$ limit concentration / pressure in heat transfer fluid (HTF)

- $H_2$ monitoring and HTF processing focused on $H_2$ removal, required to keep $H_2$ level below deterioration limit
Thermal aging of HTF causes slow hydrogen formation
Measurement of hydrogen in oil samples in solar field

**Hydrogen in gas phase**

\[
p_{H_2} = \left( V_{ges} - \frac{m_{HTF}}{\rho_{HTF}} \right) \frac{RT}{n_{H_2(g)}}
\]

\[
n_{H_2(g)} = \frac{p_{H_2}}{RT} \left( V_{ges} - \frac{m_{HTF}}{\rho_{HTF}} \right)
\]

\[
p_{H_2} = p_{ges} x_{H_2} x_{H_2} \text{ via GC}
\]

**Hydrogen in liquid phase**

\[
p_{H_2} = \frac{n_{H_2(l)}}{n_{HTF}} H_{H_2}
\]

\[
n_{H_2(l)} = \frac{p_{H_2} n_{HTF}}{H_2}
\]

- Sampling of liquid and gas phase with steel cylinders inline (pressurized & hot)
- Analysis of (all) dissolved gases offline (lab)
Gas Content: Concentration vs. Pressure

- Direct result of measurement: µmol/kg hydrogen in oil

- Receiver manufacturer’s hydrogen limit: e. g. 0.3 mbar

- Conversion from concentration to pressure via Henry coefficient (gas solubility, H, from gas dissolution experiments)

$$p_{H_2} = H_{H_2}(T) \times x_{H_2}$$
Hydrogen in Heat Transfer Fluid
Reduced Formation using Silicone Fluids?

- Eutectic mixture of biphenyl (BP) and diphenyl oxide (DPO) forms hydrogen at increasing rate on prolonged operation.
- New silicone fluids form less hydrogen on prolonged operation at elevated temperature.
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Cloud shadow prediction in CSP Plants

Optimize energetic and financial yield & plant life time

- CSP plant operation involves decisions, e.g.
  - selection of operation mode
  - tower plants: mirror focus control (avoid fast temperature changes of receiver, avoid overload dumping with dynamic aim-point selection)
  - trough plants: individual heat transfer fluid mass flow in different parts of the solar field

Andasol parabolic trough plants
Cloud Movement Analysis

irradiance maps with high temporal and spatial resolution (nowcasts and live information) from cloud camera system

• Challenges:
  • High variability
  • Complex cloud formation/motion
  • Captured at PSA
    2014- 05-28, 10:00 - 17:00

Whole Sky Imager (WSI)
Automatic solar trackers with pyrheliometer

pyranometers

+ Rotating Shadowband Irradiometers (inside PSA & 2km south)

2 Mobotix Allround M25

100 m

Image: Google, CIEMAT, DLR
Approach: Voxel carving

1. Cloud-segmentation

2. Back-projection of detected clouds view cone

3. Intersection of view cones = cloud
Approach: Voxel carving

1. Cloud-segmentation

2. Back-projection of detected clouds view cone

3. Intersection of view cones = cloud

4. Calculation of modeled shadow
Validation of modeled shadow

- Tested with ~100 cases with average ACC = 0.72
- Prototype of system (hardware + processing) running live at PSA

\[ \text{ACC} = \frac{\text{TP} + \text{TN}}{\text{surface}} \]

\[ \text{ACC} = 0.76 \]
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**Evaluation of Heliostat Field Optical Quality**

**Problem:**
Measurement of flux density distribution on aperture is not practical for large commercial (external) receivers

**Solution:**
Measurement supported simulation = Assessment of field parameters by qualification of entire heliostat field (or random samples) as basis for flux density calculation through ray tracing, verified by direct measurements

- slope
- component and system geometry
- tracking
- structural deformation
- reflectivity
- attenuation
- sun

> ray tracing simulation

<table>
<thead>
<tr>
<th>parameter(s)</th>
<th>assessment method</th>
<th>coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope (mirror shape and canting)</td>
<td>automated deflectometry</td>
<td>total/sample</td>
</tr>
<tr>
<td>structural deformation</td>
<td>on-site photogrammetry</td>
<td>sample</td>
</tr>
<tr>
<td>component and system geometry (size and positions of heliostats and receiver)</td>
<td>triangulation, stereo camera</td>
<td>sample</td>
</tr>
<tr>
<td>reflectance</td>
<td>on-site reflectometer device</td>
<td>sample</td>
</tr>
<tr>
<td>tracking accuracy</td>
<td>calibration (camera/target)</td>
<td>total</td>
</tr>
<tr>
<td>sun (DNI, sunshape)</td>
<td>on-site pyrheliometer and CCD camera</td>
<td>total</td>
</tr>
<tr>
<td>atmospheric attenuation</td>
<td>transmissometer, scatterometer</td>
<td>sample</td>
</tr>
</tbody>
</table>
Automated Deflectometry Measurement

Deflectometry (= fringe reflection): observation of deformation of regular stripe patterns through reflection

Principle:
- resolution: $10^6$ points per heliostat
- accuracy: < 0.2 mrad*

can be used for
- prototype testing
- qualification during production

Automated Deflectometry Measurement

Automated deflectometry measurement of existing heliostat field (total/samples)

- automatic selection of single heliostats/groups
- automatic measurement and data processing
- output of report and input data file for ray tracing
- performance: ~60sec./hel.

can be used for:
- field qualification during commissioning
- regular assessment of field quality during operation
High Precision Ray-Tracing of Heliostat Field

- ray tracing using deflectometry surface data in original resolution
- efficient ray generation and usage; utilization of modern cpu capabilities (SIMD, multi-threading)

→ calculation performance: $> 60 \cdot 10^6$ rays/sec using a standard pc (8 cores)

- successful validation by comparison with flux measurement*

*Belhomme et al.  
A New Fast Ray Tracing Tool for High-Precision Simulation of Heliostat Fields  
Measurement Supported Simulation of Heliostat Field

- high precision measurement systems
- calculation model covering all influence parameters
- reliability (confidence) improved by
  - high sampling rate
  - direct measurements

parameter assessment

calculation of flux distribution

support by spot meters
Application

1. During hot commissioning:
Which component is not meeting the contracted specifications?

2. During commercial operation:
Why do we perform below expectation? (... and what can we do to improve?)

- up to 100% measurement of guaranteed values
- calculation of intercept power with certain confidence level
- assessment of field and receiver efficiency

requirement: agree on measurement method and simulation model during contract negotiations

- applicable to existing systems
- continuous / repeated measurements
- updated calculation every 15-60 minutes (for monitoring)

use gathered data to optimize aim point distribution on receiver surface (next slide)
Simulation-Based Aim Point Optimization

Example: improvement of Solar Tower Jülich field performance
Ray tracing simulations based on deflectometry measurement of random samples

original heliostats
6 aim points
intercept: 0.706

new heliostat facets
same aim points
intercept: 0.828

new heliostat facets
aim point optimization
intercept: 0.861
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Open volumetric air receiver

Keyfactor air return ratio:

\[ \text{ARR} = \frac{\dot{m}_{\text{return}}}{\dot{m}_{\text{out}}} \]
Difficult measurement environment:

- High air mass flows
- High surface temperatures
- Concentrated solar radiation
- Large scales

Two approaches to measure ARR:

- Quantitative ARR measurement with tracer gas
- Qualitative ARR measurement with Induced Infrared Thermography
Tracer Gas Measurement

- Helium is used as tracer gas
- Helium is added to the system
  - Statically
  - Dynamically
- The Helium concentration response $\chi_{He}$ is measured using a mass spectrometer

Static Tracer Gas Measurement

- Both measuring points needed
- Straight forward measurement

$$\text{ARR}_{\text{stat}} = \frac{\chi_{He, in}}{\chi_{He, out}}$$

Measurement at receiver model:

$$\text{ARR}_{\text{stat}} = (61.5 \pm 2.5)\%$$
**Tracer Gas Measurement**

- Helium is used as tracer gas
- Helium is added to the system
  - Statically
  - Dynamically
- The Helium concentration response $\chi_{He}$ is measured using a mass spectrometer

**Dynamic Tracer Gas Measurement**

- Only one measuring point needed
- ARR from dynamic response
  \[
  \chi_{He,leading}(t) = A(1 - ARR^t) \\
  \chi_{He,trailing}(t) = A \cdot ARR^t
  \]

Further measurements needed:
- Circulation period $T$
- Transfer function for dynamic error correction using system identification

Measurement at receiver model:
\[
ARR_{dyn} = (63.2 \pm 4.0)\%
\]
Induced Infrared Thermography (IIT)
Summary and Conclusion

• DLR has developed a variety of tools in order to perform measurements in commercial scale trough and tower systems that go far beyond simple heat balance measurements

• All measurements have been validated in large scale facilities like the Plataforma Solar de Almería or the Research Facility Solar Tower Jülich

• Some of the measurements have been applied already in commercial full scale power plants in cooperation with the DLR Spin-off company CSP Services

• Commercial CSP applications require new methods under commercial conditions. DLR and partners have the tools and validations to provide solutions

In addition we have extensive laboratory testing facilities for industrial components …..
QUARZ Test and Qualification Center
Performance and Durability Testing

Mirror Panels
• Shape accuracy (also sag under different load conditions)
• Reflectance (specular and spectral hemispheric)
• Corrosion and abrasion tests
• Outdoor exposure at desert and coastal sites

Parabolic Trough Receiver
• Optical efficiency
• Thermal power loss
• Overheating & thermal cycling (aging of coating)
• Bellow fatigue tests (mechanical aging)
• Anti-reflective coating of glass envelope
• Operability tests under real solar conditions

Collectors
• Peak efficiency, Thermal characteristics, Incident angle modifier, behavior under different load conditions, Torsion
Thank you for your attention

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