Instrumentation and Sensors for CSP Performance Testing

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SolarPACES Task I Meeting
Cape Town, 12.10.2015
Overview

1. Motivation
2. Measurement Approaches in a Parabolic Trough Plant
3. Description of Clamp-On Systems
   I. Temperature
   II. Mass Flow Rate
4. Application of Dynamic Performance Model (PDPM) in Andasol Loop
   I. Parameterization
   II. Validation
5. PDPM approach for solar field or subfields
1. Motivation
Quantities to Measure for Thermal Performance

\[ \eta_{th} = \frac{\dot{Q}_{th}}{\dot{Q}_{Solar}} = \frac{\dot{m} \cdot c_p (T_{out} - T_{in})}{A_{net} \cdot E_b \cdot \cos(\theta) \cdot \chi^{3/2}} \]
2. Measurement approaches

**Measurement Approaches:**

(i) Standard plant instrumentation  
(ii) Embedded calibrated instrumentation  
(iii) Mobile heat unit with instrumentation and BOP  
(iv) Bypass with calibrated instrumentation  
(v) Mobile field laboratory (“Clamp On”)
2. Measurement approaches (iv)
Bypass (recommended)

- Pro
  + High measurement accuracy
  + Mounting effort (if loop prepared for bypass use)
  + Data independence

- Contra
  - Flexibility
  - Mounting effort / Leakage risk (if loop not prepared for bypass use)

Inline cp-measurement could be included in bypass.
2. **Measurement approaches** (v)
Mobile field laboratory (recommended if no bypass flanges)

**Pros**
- Flexibility
- Measurement accuracy
- No interference with plant operation
- Data independence

**Contras**
- Calibration effort
- Mounting effort (Time-consuming)
3. Clamp-On: Temperature

- Class-A Pt100 with 4 wire connection
- Good thermal coupling realized through brass block, thermal conductive paste and hose clamps (torque 15 Nm)
- Homogenized temperature in the direct environment of the sensor via brass block
- Reduction of environmental influences through copper shield and insulation

1) Pipe
2) Reference PT100 sensors
3) ClampOn PT100 sensor with copper block
4) Copper temperature shield
5) Insulation
3. Clamp-On: Temperature
Temperature Diff. between Inline and ClampOn (uncorrected)

Temperature difference \( \Delta T = T_{\text{ref}} - T_{\text{clamp on}} \)

\[
y = 3.840 \times 10^{-6} x^2 + 6.676 \times 10^{-4} x + 1.360 \times 10^{-1}
\]

Systematic measurement noise:
- @100°C: \( \pm 0.26°C \)
- @390°C: \( \pm 0.40°C \)

Only Reynolds numbers \( \geq 30000 \)
### 3. Clamp-On: Temperature

Remaining Uncertainty of ClampOn Temperature Measurement After Correction

<table>
<thead>
<tr>
<th>Inline Reference $T_{ref}$ 2xPT100 redundant measurement of $T_{fluid}$</th>
<th>Uncertainty ($T_{ref}$)</th>
<th>ClampOn $T_{CO, w/}$ with correction</th>
<th>Uncertainty ($T_{CO, w/}$) incl. systematic uncertainty of ClampOn method</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.67 °C</td>
<td>±0.16° K</td>
<td>100.72 °C</td>
<td>±0.34° K</td>
</tr>
<tr>
<td>150.83 °C</td>
<td>±0.18° K</td>
<td>150.61 °C</td>
<td>±0.43° K</td>
</tr>
<tr>
<td>200.45 °C</td>
<td>±0.21° K</td>
<td>200.19 °C</td>
<td>±0.49° K</td>
</tr>
<tr>
<td>250.52 °C</td>
<td>±0.26° K</td>
<td>250.22 °C</td>
<td>±0.50° K</td>
</tr>
<tr>
<td>300.58 °C</td>
<td>±0.28° K</td>
<td>300.81 °C</td>
<td>±0.54° K</td>
</tr>
<tr>
<td>350.78 °C</td>
<td>±0.31° K</td>
<td>350.55 °C</td>
<td>±0.60° K</td>
</tr>
<tr>
<td>390.95 °C</td>
<td>±0.33° K</td>
<td>390.78 °C</td>
<td>±0.62° K</td>
</tr>
</tbody>
</table>

- Uncertainty of ClampOn measurement is only doubled compared to inline PT100
- Uncertainty of ClampOn-measurement technique remain below 0.6 K.
3. Clamp-On: Temperature
Temperature Correction ClampOn

- Correction reduces uncertainty significantly
- Dimensionless approach is being developed to correct clampOn temperature also for other fluids and ambient conditions

Correction $\Delta \Theta_{P-f}$

$$\Delta \Theta_{P-f} = a_1 \cdot (Re + dm)^m \cdot (Pr + dn)^n \cdot (\Delta \Theta_{f-amb})^p \cdot (Bi + dq)^q \cdot (\lambda_{iso}/\lambda_f)^s \cdot (\delta_P/d_i)^u \cdot (\delta_{iso}/d_i + dv)^v$$
3. Clamp-On: Volume Flow

- Fluid flow measured via travel time differences of ultrasonic signals
- Ultrasonic signal is acoustically coupled to the pipe
- For T>200° C: Sensor heads thermally decoupled via wave injector from pipe
- Pipe geometry and material properties (pipe and HTF) included in calculation

- Uncertainty of ultrasonic mass flow measurement remain 1.4% of mass flow rate

SCNR value for both channels constantly in an area of 28 DB to 32 DB.
4. Parameterized Dynamic Performance Model (PDPM) applied in Andasol Loop

Modelling approach for parameter identification from test data for field performance prediction for given field parameters and ambient conditions.

\[
\dot{Q}_h = \chi \frac{h}{c} \cdot A_{net} \cdot E_b \cdot \cos(\theta) \eta_{opt,0} \cdot \kappa(\theta) \cdot f_{endless} \cdot f_{shade} \cdot f_{focus} - c_1 \cdot (T_m - T_{amb}) - c_2 \cdot (T_m - T_{amb})^2 - c_3 \frac{dT_m}{dt}
\]

with

\[
\kappa(\theta) = 1 - b_1 \theta - b_2 \theta^2
\]

Residence time effects are considered through a CSTR model (continuous stirred tank reactor). Perfect mixing of fluid in each tank is assumed.

<table>
<thead>
<tr>
<th>coefficients</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_{opt,0})</td>
<td>optical efficiency</td>
</tr>
<tr>
<td>(b_1, b_2)</td>
<td>IAM coefficients</td>
</tr>
<tr>
<td>(c_1, c_2)</td>
<td>thermal loss coefficients</td>
</tr>
<tr>
<td>(c_3)</td>
<td>specific heat capacity coefficient</td>
</tr>
</tbody>
</table>

Time stamp i-1

\[
m_i^t = (m_{i-1}^t - \Delta m_{i-1}^t) + \Delta m_{i-1}^t
\]

\[
h_i^t = \frac{m_{i-1}^t h_{i-1}^t + \Delta m_{i-1}^t h_{i-1}^t}{m_i^t}
\]

\[
T_i^t = f(h_i^t), \quad \rho_i^t = g(h_i^t)
\]

\[
\Delta m_i^t = \rho_i^t \cdot V_i
\]
4. Parameterized Dynamic Performance Model (PDPM)
Parameterization Data Set (Andasol Loop), backward approach

Mass flow reduction

Day 1: 30.03.2015
Day 2: 31.03.2015

HTF enthalpy flow rate in kW

DNI in W/m²

14:00 15:00 16:00 17:00
Time in HH:MM

11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00
Time in HH:MM
4. Parameterized Dynamic Performance Model (PDPM)
Validation Data Set (Andasol Loop), forward approach

- Indepandant validation data set which was not used to identify parameters
- Good agreement: Deviation in integrated enthapy flow over plotted period: ~0.4%
5. PDPM approach for solar field or subfields

- Condensing all parallel loops into one average loop
- Only overall performance characteristics, no individual loop characteristics
- Target quantity: Thermal power of solar subfield, not of individual loops
THANK YOU for your attention.

THANK YOU to the team.

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THANK YOU for the support.

We gratefully acknowledge the financial support from the German Federal Ministry for Economic Affairs and Energy and DIN/DKE for the projects:
- STAMEP 0325472A.
- INS 1284.

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DLR Qualification
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