HEAT FLUX MEASUREMENT ON CSP

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Central receiver

Tower

Heliostat field
CAMERA / TARGET METHOD: Indirect Heat Flux Measurement

- CCD camera: 14 bit digitization
  1024 x 1280 pixels (pixel size: 6.7 µm x 6.7 µm)
  Spatial resolution: 2 mm
- Lambertian target.
- Water cooled radiometer (Ø 25, 15 mm)
- From gray levels to kW/m².
- Accuracy of radiometers: ± 3-4%
- Accuracy of the power measurement: ± 5-6%
ProHERMES 2A CALIBRATION FUNCTION FOR HITREC II RECEIVER

Date: 30-01-2001. Calorimeter 7016

\[ y = 0.0271 \times -5.9573 \]
\[ R^2 = 0.9942 \]
MDF  Direct Heat Flux Measurement

• Array of themopiles (HFM radiometers).

• Small area (Ø 6.32 mm)

• Response time ~ 10 microseconds.
  Measuring without water-cooling.

• Accuracy of radiometers ± 3%

• Accuracy of the power measurement ± 5-6%
Water-cooled radiometers (Thermogage)

Receiver aperture

Hot fingers

HFM radiometers

0.880 m

1.070 m

1.045 m
Receiver aperture
Reference radiometer
HFM radiometers
Hot fingers
Rotary rod
Signal from the reference HFM radiometer
Hitrec II receiver aperture
≈ 300 data
≈ 4000 data

\[ P = \frac{A}{n} \sum_{i=1}^{n} F_i \]
Direct system (MDF) \textit{versus} Indirect system (ProHERMES 2)
• After several improvements to the original device, the system has become one-click heat flux measurement equipment.

**RELEVANT QUANTITIES ASSOCIATED WITH THE IMAGE**

DATE: 2009/07/21  
LOCAL TIME: 13:17  
DNI: 888 W/m²  
Nº HELIOSTATS: 45  

- Number of measured data = 96  
- Number of interpolated data = 533  
- Flux peak = 1147 kW/m²  
- xmax = 0.200 m  
- ymax = -0.050 m  
- Total Power = 857 kW  
- Power Error = ± 38 kW  
- Power Error = ± 4.5%  
- Flux Average = 649 kW/m²  
- Energy = 0.44 kWh  
- Scanning Time = 1.86 s  

Heat flux distribution 2D onto receiver aperture.
Advantages and disadvantages

- Spatial resolution
- Simplicity
- Accuracy
How to measure in a non-plane receiver aperture?
SUMMARY 1

• A hybrid system and procedure for measuring the incident power on the aperture of solar receivers have been demonstrated.

• The advantages of each of the approaches enrich the overall system and thereby the measurements made with it.

• Working with both systems, it is possible to detect changes in their calibration.

• The good agreement between the two methods allows the use of a heat-flux measurement system based on either the direct or the indirect concept or hybridized, depending on the receiver geometry and the size of the area to be scanned.
GARDON RADIOMETER

\[ Q_{in} \]

- Constantan foil
- Copper body
- Copper wires
- Output voltage

Ti
Calibration by using dual cavity black-body
Stefan-Boltzmann law; $\Delta T \rightarrow \text{heat flux error} \propto (\Delta T)^3$
Comparison of radiometers in the laboratory
Normalized Spectral Distribution (1353 W/m², Solar constant)

- AM0
- AM1
- AM2
- AM5
- Black body 850 °C
- Black body 5727 °C
- Zynolyte
- Colloidal graphite

Absorptance

Spectral Irradiance (W/m²µm)

Wavelength (µm)

0 1 2 3 4 5 6 7 8 9 10

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Zynolyte

Colloidal graphite
Zynolyte:
• The sensor overestimates the solar irradiance by 3.6%
• Solar absorbance 95.4 %

Colloidal graphite:
• Coating used over 3500 kW m\(^{-2}\).
• The sensor overestimates the solar irradiance by 27.9%
• Solar absorbance 84.7 %

CAREFUL WITH SYSTEMS EVALUATED OVER 3500 kW m\(^{-2}\)
Calibration using a thermal balance
Calibration using a thermal balance
Water flow: 1 litre min$^{-1}$
Inlet temperature: 14°C

Equation: $y = B \times x$

$R^2 = 0.99948$

$B = 111.9 \pm 0.3 \text{ kW m}^{-2} \text{ mV}^{-1}$
<table>
<thead>
<tr>
<th>Water flow (liter.min(^{-1}))</th>
<th>Inlet Temperature (°C)</th>
<th>B (kW.m(^{-2}).mV(^{-1}))</th>
<th>ΔB (kW.m(^{-2}).mV(^{-1}))</th>
<th>Uncertainty %</th>
<th>(R^2)</th>
<th>Repetability %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>15.5</td>
<td>110.1</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9954</td>
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<td>111.9</td>
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<td>111</td>
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<td>110</td>
<td>0.3</td>
<td>0.3</td>
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<tr>
<td>1.6</td>
<td>15.0</td>
<td>110.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.9980</td>
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</table>
SUMMARY 2

• An alternative method of calibrating high-heat flux sensors by thermal balance has been presented. The results are in agreement with calibrations obtained using black-body radiation. However, the proposed method has the potential of being more accurate than traditional approaches.

• This new procedure calibrates sensors to correctly measure under conditions of concentrated solar radiation.

• At present, the thermal balance calibration technique in the laboratory is limited to solar irradiances of approximately 100 kW m\(^{-2}\). The next step is to demonstrate this methodology to higher irradiances under non-laboratory conditions in the CIEMAT solar furnace at Plataforma Solar de Almería.
Thermal balance calibration
Thermal balance calibration
# 7915, Zynolyte

Water flow: 2 liter min$^{-1}$
Inlet temperature: 29.2 °C

Irradiance / kW m$^{-2}$

Equation: $y = B \times$
$R=0.99994$
$B=112.6 \pm 0.5$ kW m$^{-2}$ mV$^{-1}$

# 7918, Colloidal graphite (Electrodag 154)

Water flow: 2.5 liter min$^{-1}$
Inlet temperature: 21.8 °C

Irradiance / kW m$^{-2}$

Equation: $y = B \times$
$R=0.99992$
$B=414 \pm 3$ kW m$^{-2}$ mV$^{-1}$
Table 1. Calibration of a Gardon sensor (# 7915, Zynolyte)

<table>
<thead>
<tr>
<th>Water flow (liter min⁻¹)</th>
<th>Inlet temperature (°C)</th>
<th>B (kW m⁻² mV⁻¹)</th>
<th>ΔB (kW m⁻² mV⁻¹)</th>
<th>Uncertainty %</th>
<th>R</th>
<th>SE %</th>
<th>ΔSE %</th>
</tr>
</thead>
<tbody>
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<td>1.5</td>
<td>29.5</td>
<td>111.4</td>
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<td>0.99991</td>
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<td>112.6</td>
<td>0.5</td>
<td>0.4</td>
<td>0.99994</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>2.5</td>
<td>29.4</td>
<td>113.6</td>
<td>0.6</td>
<td>0.5</td>
<td>0.99995</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2. Calibration of a Gardon sensor (# 7918, Colloidal graphite)

<table>
<thead>
<tr>
<th>Water flow (liter min⁻¹)</th>
<th>Inlet temperature (°C)</th>
<th>B (kW m⁻² mV⁻¹)</th>
<th>ΔB (kW m⁻² mV⁻¹)</th>
<th>Uncertainty %</th>
<th>R</th>
<th>SE %</th>
<th>ΔSE %</th>
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<td>3</td>
<td>0.7</td>
<td>0.99992</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>
SUMMARY 3

• This procedure has enabled these sensors to be calibrated under concentrated solar radiation at high irradiances in the CIEMAT solar furnace at the Plataforma Solar de Almería.

• Working at high irradiances (1000 kW m<sup>-2</sup>) has allowed the uncertainty of the calibration constant of these sensors to be reduced. ± 3-4 %............±1-2 %

• This work has experimentally confirmed the predicted systematic errors in measuring high solar irradiances using Gardon sensors calibrated with a black body.