Accelerated Ageing of Solar Receiver Coatings: Experimental Results for T91 and VM12 Steel Substrates

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Outline

• Introduction
  • Solar receiver coatings
  • Degradation mechanisms
• Optical Characterization
  • Solar absorptance
  • Thermal emittance
• Experimental setups
  • Solar cycling tests
  • Climate test chambers
• Results and discussion
• Conclusion & Outlook
Introduction

Solar receiver coatings (1)

• State of the art:
  • Pyromark 2500 (Tempil)
    • “Silicon based coating for metals”
    • “Long lasting vs. oxidation and corrosion”
    • “Withstands high temperature, 1093 °C”
  • High nominal solar absorptivity of 0.95
  • High thermal emittance
    • ~ 0.8 at 100 °C to 0.9 at ~1000 °C

• Reality:
  • Poor durability
  • Max. temp. ~ 750 °C
  • High thermal emittance

• New coating formulations:
  • Coating A:
    • ceramic paint, spray
  • Coating B:
    • protective slurry aluminide + coat. A (top)
  • Coating C:
    • sputtered on polished substrate
    • selective coating (low thermal emittance)
  • Coating D:
    • multi-metallic diffusion coating
    • based on Chromium (Cr) and Manganese (Mn)
Introduction
Solar receiver coatings (2)

• Four different metal substrates
  • End Applications:
    • Solar Receiver Steam Generator (SRSG)
    • Molten Salt Receiver (MSR)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Solar cycling (Tube samples)</th>
<th>Climate chambers (Flat samples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T91/P91</td>
<td>Overheated</td>
<td>Completed</td>
</tr>
<tr>
<td>VM12</td>
<td>100+ cycles</td>
<td>In progress</td>
</tr>
<tr>
<td>T22</td>
<td>Start: Mid-October 2017</td>
<td>Start: Mid-October 2017</td>
</tr>
<tr>
<td>Inc-617</td>
<td>Schedule: Early 2018</td>
<td>Schedule: Early 2018</td>
</tr>
</tbody>
</table>

• Flat and tubular sample geometries

VM12 tubes, Before exposure
Introduction
Solar receiver coatings (3)

- Identified degradation mechanisms

- **Effects:**
  - Optical fading
    - Loss of solar absorptance
    - Gain of thermal emittance
  - Gain of thermal emittance

- **Causes:**
  - Corrosion ("red dots")
  - Hot oxidation ("white dots")
  - Flaking / delamination / cracks

- **Goal:** Reproduce mechanisms
  - Outdoor: Dish test facility
  - Indoor: Climate test chambers
Optical Characterization
Solar weighted absorptance

• Weighting formula:

\[ \alpha_s = \frac{\int_{\lambda_1}^{\lambda_2} [1 - R(\lambda)] \cdot G_{\text{sol}}(\lambda) \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} G_{\text{sol}}(\lambda) \cdot d\lambda} \]

• Spectrophotometer:
  • Perkin Elmer Lambda1050
  • UV-VIS-NIR; 0.28 to 2.5 µm
  • Incidence angle: 8°
  • Integration sphere Ø: 150 mm

ASTM G173-03 (direct)

Spectral irradiance (W m⁻² nm⁻¹)

Wavelength (nm)

Extraterrestrial Radiation (AM0)  Direct Normal Irradiance (AM 1.5)

UV-VIS-NIR, spectral data

Wavelength (nm)

Coating A  Coating B  Coating C  Coating D  Bare substrate  Polished substrate
Optical Characterization

Thermal emittance (1)

Weighting formula:

\[
L_{BB}(\lambda, T) = \frac{2\pi h c^2}{\lambda^5 \cdot \exp\left(\frac{hc}{\lambda kT}\right) - 1}
\]

\[
\varepsilon_{\text{th}}(T) = \frac{\int_{\lambda_1}^{\lambda_3} \left[1 - R(\lambda)\right] L_{BB}(\lambda, T) \cdot d\lambda}{\int_{\lambda_1}^{\lambda_3} L_{BB}(\lambda, T) \cdot d\lambda}
\]

- **Spectrophotometer:**
  - Frontier FTIR, Pike int. sphere
  - NIR-MIR; 2 to 16 µm
  - Incidence angle: 12°
  - Integration sphere Ø: 76.2 mm

### Spectral Range

- Coating A
- Coating B
- Coating C
- Coating D
- Bare substrate
- Polished substrate

### Spectral Range: 0.28 to 16 µm

(\(\sim 97\% \sigma \) at 650 °C)
Optical Characterization

Thermal emittance (2)

Planck's law

\[ L_{\text{em}}(\lambda, T) = \frac{2\pi \hbar c^2}{\lambda^5} \cdot \exp\left(\frac{\hbar c}{\lambda kT}\right) - 1 \]

Surface preparation; polished vs. bare substrate

![Graph showing thermal emittance vs. absorber temperature with different coatings and substrate types.](chart8)
Optical Characterization
Performance criterion & initial values

• Thermal efficiency

\[
\eta_{coating} = \frac{\alpha_s Q_{sol} - \varepsilon_{th} \cdot \sigma \cdot T_{abs}^4}{Q_{sol}}
\]

\[
\frac{d\eta_{coating}}{d\alpha_s} = \frac{d\eta_{coating}}{d\varepsilon_{th}} = -\frac{\sigma \cdot T_{abs}^4}{Q_{sol}}
\]

• Default values:
  • \(Q_{sol} = 250\ kW/m^2; T_{skin} = 650\ ^\circ C\)
  • Trade-off: +1\% \(\alpha_s \sim -16.5\% \varepsilon_{th}\)

• Goals:
  • Solar absorptance \sim 96\%
  • Max. acceptable loss: - 0.5\%
  • Maximize thermal efficiency

<table>
<thead>
<tr>
<th>Substrate</th>
<th>VM12 – Tubular samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating</td>
<td>(\alpha_s) (%)</td>
</tr>
<tr>
<td>Coating A</td>
<td>96.2 (\pm 0.3)%</td>
</tr>
<tr>
<td>Coating B</td>
<td>95.3 (\pm 0.3)%</td>
</tr>
<tr>
<td>Coating C</td>
<td>95.1 (\pm 0.4)%</td>
</tr>
<tr>
<td>Coating D</td>
<td>93.2 (\pm 0.3)%</td>
</tr>
<tr>
<td>Bare substrate</td>
<td>71.7%</td>
</tr>
<tr>
<td>Polished substrate</td>
<td>44.7%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substrate</th>
<th>T91 – Flat samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating</td>
<td>(\alpha_s) (%)</td>
</tr>
<tr>
<td>Coating A</td>
<td>96.4 (\pm 0.0)%</td>
</tr>
<tr>
<td>Coating B</td>
<td>96.7 (\pm 0.1)%</td>
</tr>
<tr>
<td>Coating C</td>
<td>94.8 (\pm 0.2)%</td>
</tr>
<tr>
<td>Coating D</td>
<td>91.7 (\pm 0.6)%</td>
</tr>
<tr>
<td>Bare substrate</td>
<td>N.A.</td>
</tr>
<tr>
<td>Polished substrate</td>
<td>N.A.</td>
</tr>
</tbody>
</table>
Solar Cycling Tests

Experimental test bench

- **Dish test facility** (Distal II, PSA)
  - 15 tubular samples at a time
  - 5 parallel strings of 3 probes

- **Flux control:**
  - Linear drive (master)

- **Temp. control:**
  - Air blowers (slaves)

- **Sensors:**
  - Water cooled radiometer
  - Thermocouples type K
Solar Cycling Tests
Temperature measurement

• Embedded thermocouples (Type K)

- \( \Delta T \) along wall thickness (1.9 +/- 0.1 mm)
- - 30 K for coatings A, B and D
- - 18 K for coating C (thinner coating)

• Solar blind infrared camera:
  - Optris PI640 G7, 7.9+/− 0.3 \( \mu \)m
  - To be implemented end of 2017
Solar Cycling Tests

Test conditions

- **Test profiles:**
  - 650 °C max. skin temperature
  - Min. 250 kW/m² on samples

- **Total # cycles:**
  - 100 cycles (paper)
  - 150 cycles (Mid-September)
Environmental Test Chambers

Test conditions

• Four independent tests on flat samples:
  • Damp Heat (DH)
  • Condensation (Cond.)
  • Humidity Freeze (HF)
  • Neutral Salt Spray (NSS)

### TABLE 2
Summary of climate chamber test conditions for Condensation, Damp Heat (DH), Humidity Freeze (HF) and Neutral Salt Spray (NSS). For each coating, 3 flat samples are exposed in the corresponding climate test chamber.

<table>
<thead>
<tr>
<th>Test</th>
<th>Condensation</th>
<th>Damp Heat (DH)</th>
<th>Humidity Freeze (HF)</th>
<th>Neutral Salt Spray (NSS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>480 hours</td>
<td>1000 hours</td>
<td>1500 hours</td>
<td>480 hours</td>
</tr>
<tr>
<td>Conditions</td>
<td>$T_{\text{amb}}$: 40 °C</td>
<td>$T_{\text{amb}}$: 65 °C</td>
<td>$T_{\text{amb}}$: -40 to 65 °C</td>
<td>$T_{\text{amb}}$: 35 °C</td>
</tr>
<tr>
<td></td>
<td>RH: 100 %</td>
<td>RH: 85 %</td>
<td>RH: max. 85%</td>
<td>pH 6.5 to 7.2 at 25 °C</td>
</tr>
</tbody>
</table>
Experimental results
Solar cycling tests

• Observations:
  • No significant optical degradation observed after 100 cycles for A,B,C,D
  • Early oxidation of ref. uncoated samples

• Ranking:
  • Highest solar absorptance: Coatings A,B,C (> 95%)
  • Highest thermal efficiency: Coating C (91 %)
  • Coatings A and B have similar efficiencies (~ 85%)
  • Coating D performance had to be improved
Experimental results

Solar cycling tests

Coating A

Coating B

Coating C

Coating D

Polished

Bare substrate
Experimental Results

Climate Chamber Tests

**Observations:**
- Coatings A, B passed all tests
  - Par efficiency (85%)
- Coating C still ranks 1st in efficiency
  - ... but it failed NSS test
- Coating D only passed DH test

<table>
<thead>
<tr>
<th>T91</th>
<th>COND</th>
<th>DH</th>
<th>HF</th>
<th>NSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating A</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Coating B</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Coating C</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>❌</td>
</tr>
<tr>
<td>Coating D</td>
<td>❌</td>
<td>✔️</td>
<td>❌</td>
<td>❌</td>
</tr>
</tbody>
</table>
Conclusion

• Solar cycling test (VM12):
  • No significant degradation after 100 cycles
  • First signs of degradation started to show up after 150 cycles and “dust rain” event

• Climate chamber tests (T91):
  • Coatings A,B passed all tests
  • Coatings C,D did not pass NSS

• Coating comparison:
  • Performance: Coatings A,B,C
  • Durability: Coatings A and B
  • LCOC: Coating A (spray)
  • Coating C has the highest efficiency (selective)
  • Coating D performance had to be improved

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<tr>
<td>Coating</td>
<td>$\alpha_r$ (%)</td>
<td>$\varepsilon_{th,650^\circ C}$ (%)</td>
</tr>
<tr>
<td>Coating A</td>
<td>96.2 ± 0.3 %</td>
<td>71.7 ± 1.2 %</td>
</tr>
<tr>
<td>Coating B</td>
<td>95.3 ± 0.3 %</td>
<td>63.0 ± 0.7 %</td>
</tr>
<tr>
<td>Coating C</td>
<td>95.1 ± 0.4 %</td>
<td>22.4 ± 0.6 %</td>
</tr>
<tr>
<td>Coating D</td>
<td>93.2 ± 0.3 %</td>
<td>70.6 ± 1.8 %</td>
</tr>
<tr>
<td>Bare substrate</td>
<td>31.7%</td>
<td>40.3%</td>
</tr>
<tr>
<td>Polished substrate</td>
<td>44.7%</td>
<td>12.3%</td>
</tr>
</tbody>
</table>

Dish – After 100 cycles
Thank you for your attention!

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[Website Link]  
https://www.raiselife.eu/