Development of an innovative thermal energy storage (TES) solution for middle-size concentrated solar power (CSP) plant

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Funding:

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Introduction

Objectives

Experimental work

• Selection of the storage material

• Structural characterization

• Thermophysical properties

• Mechanical properties

• Corrosion and compatibility study

Conclusions

Perspectives
## Background of the project

The CSP-ORC (1 MWel) commercial power plant characteristics:

<table>
<thead>
<tr>
<th>Plant location</th>
<th>Benguerir, Morocco</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Normal Irradiance</td>
<td>2100 kWh/m²/year</td>
</tr>
<tr>
<td>Solar field (SF) heat transfer fluid</td>
<td>Delcoterm Solar E15 (Mineral oil)</td>
</tr>
<tr>
<td>SF inlet/outlet temperature</td>
<td>180 - 300 °C</td>
</tr>
<tr>
<td>ORC working fluid</td>
<td>Cyclopentane</td>
</tr>
<tr>
<td>ORC Gross output</td>
<td>1 MWel</td>
</tr>
<tr>
<td>ORC design point efficiency</td>
<td>20 %</td>
</tr>
<tr>
<td>Storage</td>
<td>No</td>
</tr>
</tbody>
</table>

### Overview of the Green Energy Park

### Power block of the plant

### North side of the solar field
The aim of the ORC-Plus project

Develop a TES solution adapted to 1 – 5 MWel CSP plants:

- Extension of the solar field to feed the storage system.
- Validation of thermocline TES Prototype of 200 kWh$_{th}$ at laboratory scale.
- Construction of commercial TES system of 20MWh$_{th}$ (4 hours of storage) for the CSP-ORC power plant at Green Energy Park in Ben-Guerir, Morocco.

Integration of a novel thermal storage system

- Technology: Thermocline
- Capacity: 20 MWth
- Duration: 4 h

HTF: mineral oil
$T_{\text{min}}$: 180 °C
$T_{\text{max}}$: 300 °C

1MW commercial CSP-ORC plant located in Green Energy Park Benguerir, Morocco

SF1: 7 loops to feed ORC
SF2: 3 loops to charge TES

Extension of the solar field

Linear Fresnel reflectors
The aim of the ORC-Plus project

TES prototype of 200 kWth (1/100 industrial scale) to validate the technology:

Solid packed-bed thermocline system is under development and testing at laboratory scale.

- Storage based on natural stratification of temperature.
- Two materials in direct contact in the same tank:
  - Filler (packed bed): ceramic material
  - Heat transfer fluid: liquid (oil or molten salt) or gas (Air)

<table>
<thead>
<tr>
<th>Developer</th>
<th>CIC Energigune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Packed-bed thermocline</td>
</tr>
<tr>
<td>Total energy capacity (kWh&lt;sub&gt;th&lt;/sub&gt;)</td>
<td>200</td>
</tr>
<tr>
<td>Storage volume</td>
<td>2 m³</td>
</tr>
<tr>
<td>Filler material</td>
<td>Solid material</td>
</tr>
<tr>
<td>Heat Transfer Fluid (HTF)</td>
<td>Delcoterm Solar E15 (mineral oil)</td>
</tr>
<tr>
<td>Temperature range</td>
<td>180°C-300°C</td>
</tr>
</tbody>
</table>
Selection of the storage material

Valorisation of different classes of ceramic materials:

- To obtain a viable and cost-effective TES material,
- To reduce the industrial environmental impact.

Material requirements for TES:

- Low cost ceramic materials,
- Appropriate thermophysical properties,
- Good thermal stability,
- Good mechanical behaviour,
- Good thermomechanical stability,
- Compatible with the heat transfer fluids.

BOF-Slag (by-product)  Magnetite (mineral)  River Rock (local natural rock)
Structural characterization

Chemical Composition (ICP - OES)

<table>
<thead>
<tr>
<th>Material</th>
<th>Element (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al</td>
</tr>
<tr>
<td>BOF-Slag</td>
<td>1.2</td>
</tr>
<tr>
<td>Magnetite</td>
<td>0.2</td>
</tr>
<tr>
<td>River Rock</td>
<td>3.44</td>
</tr>
</tbody>
</table>

SEM & EDX analyses

multi-phases

BOF-Slag

mono-phase

Magnetite

multi-phases

River Rock

Perpignan, June 14th, 2017
Thermophysical properties

Thermal conductivity

- The thermal conductivity at 100°C is around 1.9, 2.8 and 3.4 W/m.K for BOF-Slag, River rock and Magnetite, respectively.
- Slight decrease with temperature is obtained.

The evolution of the thermal conductivity with temperature
Thermophysical properties

Specific heat $C_p$

![Graph showing specific heat $C_p$ versus temperature for various materials.](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$C_p$ (J/g.K)</th>
<th>Volumetric Storage Capacity (KJ/m$^3$.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOF-Slag</td>
<td>3806</td>
<td>0.91</td>
<td>3446</td>
</tr>
<tr>
<td>Magnetite</td>
<td>4962</td>
<td>0.89</td>
<td>4416</td>
</tr>
<tr>
<td>River rock</td>
<td>2616</td>
<td>1.08</td>
<td>2825</td>
</tr>
<tr>
<td>Alumina</td>
<td>3953</td>
<td>0.88</td>
<td>3478</td>
</tr>
<tr>
<td>Cofalit</td>
<td>3120</td>
<td>0.90</td>
<td>2808</td>
</tr>
<tr>
<td>HT Concrete</td>
<td>2250</td>
<td>0.92</td>
<td>2070</td>
</tr>
</tbody>
</table>

Specific Heat $C_p$ of BOF-Slag, Magnetite and River rock
Mechanical properties

Compressive Strength

- The compression tests were carried out using a test speed of 3 mm/min and load cell of 100 KN.
- The compressive yield strength (σ) was calculated by:
  \[ \sigma = \frac{F}{A} \]
  
  - F: Load at yield,
  - A: Cross-section area.
- The maximum compressive strength at RT are 357, 193 and 85 MPa for BOF-Slag, Magnetite and River rock, respectively.
Mechanical properties

Compressive Strength

Compressive Strength after thermal cycling

<table>
<thead>
<tr>
<th>BOF-Slag As-received</th>
<th>Magnetite</th>
<th>River rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength (MPa)</td>
<td>357</td>
<td>157</td>
</tr>
<tr>
<td>As-received</td>
<td>183</td>
<td>142</td>
</tr>
<tr>
<td>After 250 cycles</td>
<td>48%</td>
<td>9%</td>
</tr>
</tbody>
</table>

Perpignan, June 14th, 2017
Mechanical properties

Compressive Strength

Compressive Strength after thermal cycling

The reasons:
- The gradient of the temperature due to the limited thermal conductivity,
- The multi-phases constitutions with different thermal expansion coefficients.

The magnetite presents high thermal conductivity and mono-phase constitution which may responsible of its good thermomechanical behaviour.

Perpignan, June 14th, 2017
Corrosion & compatibility study

Systems and conditions
- Isothermal mode: at 310 °C for 500h, 1000, 1500 and 3000 hours
- Cycling mode: between 180°C and 310°C with heating rate of 10°C.min-1
- Time: 500, 1000, 1500 and 3000 hours

HTF

Delcoterms Solar E15

Ceramic materials
- Magnetite

Container Material
- Carbon steel A 516
- Stainless steels 304 and 316
Corrosion & compatibility study

Methods

Static

- Magnetite
- Alumina crucible
- Copper gasket
- Steel reactor
- Oil
- Furnace chamber

Dynamic

- High-pressure reactor
- Oil

In-situ
Corrosion & compatibility study

Results: Magnetite + Delcoterem Solar E15 Oil at 310°C

- Magnetite: no significant modifications were detected
- Oil: no structural changes and no thermophysical properties modifications were observed

The Magnetite and Delco Term oil are fully compatible to operate in direct contact up to 310°C
The Magnetite is very promising material:

- **High volumetric** energy storage capacities: 4416 kJ/m$^3$.K,
- High values of the **thermal conductivity**: $>2.5$ W/m.K,
- Good **thermo-stability** in the operation temperature range,
- Good **mechanical** properties of **as-received materials** at room temperature.
- Good **thermo-mechanical** stability up to 250 cycles in the operation temperature range
- **Fully compatible** with the HTF (DelcoTem Oil) in the operation temperature range.

This material can be considered as the most promising candidate for effective thermal energy storage.
Perspectives

Design, realization and commissioning of the trial TES system

The construction of the system based on Magnetite pebbles as storage media is already constructed and under testing.

- Useful volume for storage: 2.07 m$^3$
- Aspect ratio = 2 (H/D)
- Useful dimensions: D=1.097 m & H =2.194 m
- Void fraction = 0.37

**Storage material: Magnetite**

Density: 4962 kg/m$^3$
Mass: 6468 kg
Cp:0.85 J/g.K
$\Delta T$=120 K
Energy stored in Magnetite: 119 kWh

**Oil:**

Density: 675 kg/m$^3$
Cp: 2.68 kJ/(kg.K)
Energy stored in the oil: 80 kWh

**TOTAL:** 199 kWh$^{th}$
Thank you for your attention